

MiniBooNE First Neutrino Oscillation Results

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on behalf of the MiniBooNE Collaboration

IFIC Seminar, Valencia, April 19th 2007

Outline

Motivation

MiniBooNE neutrino beam, detector, events

Closed electron neutrino box era (2002 – March 2007):

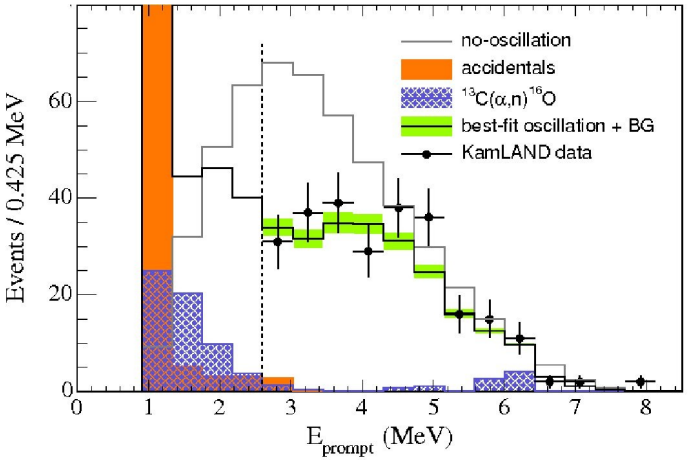
- Tuning experiment's simulations, event reconstruction, and PID
- Constraining electron neutrino backgrounds with data
- Systematic uncertainties and cross-checks

Open electron neutrino box era (March 2007 - present):

- Electron neutrino candidate events
- Result on muon-to-electron neutrino oscillations

Conclusions and the next steps

Neutrino Oscillation Signatures

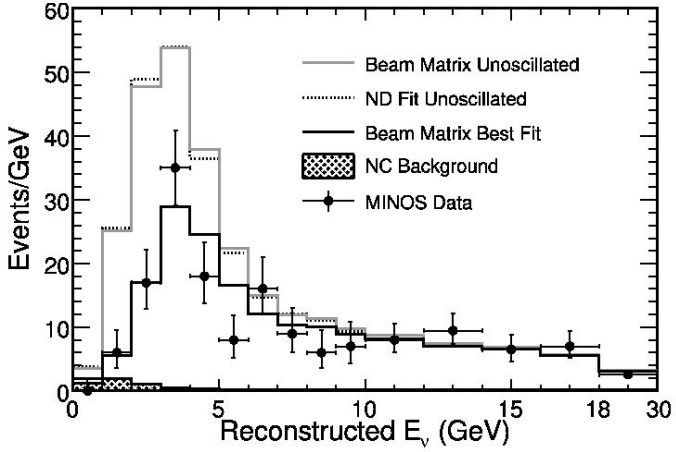


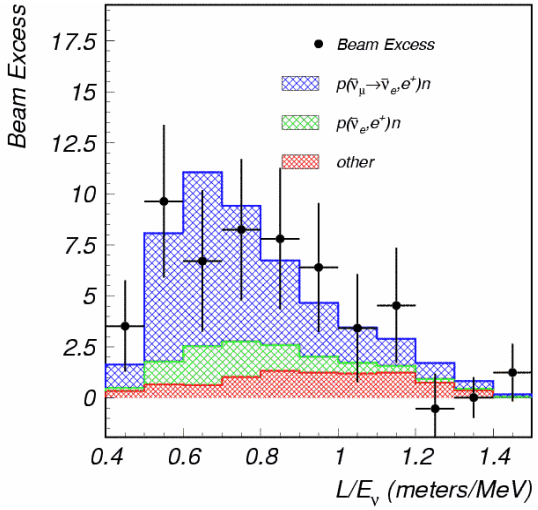
Solar Neutrino Oscillations

- Deficit of nues observed from the Sun
  Homestake, SAGE, GALLEX/GNO, Super-K, SNO
- Confirmed by KamLAND (reactor nuebars)

Atmospheric Neutrino Oscillations

- Zenith angle-dependent deficit of atmospheric numus
  Kamioka, Super-K, Soudan, MACRO
- Confirmed by K2K and MINOS (accelerator numus)





LSND Neutrino Oscillations

- Excess of nuebars in numubar beam produced from muon decay-at-rest
- Unconfirmed by other experiments, but not excluded

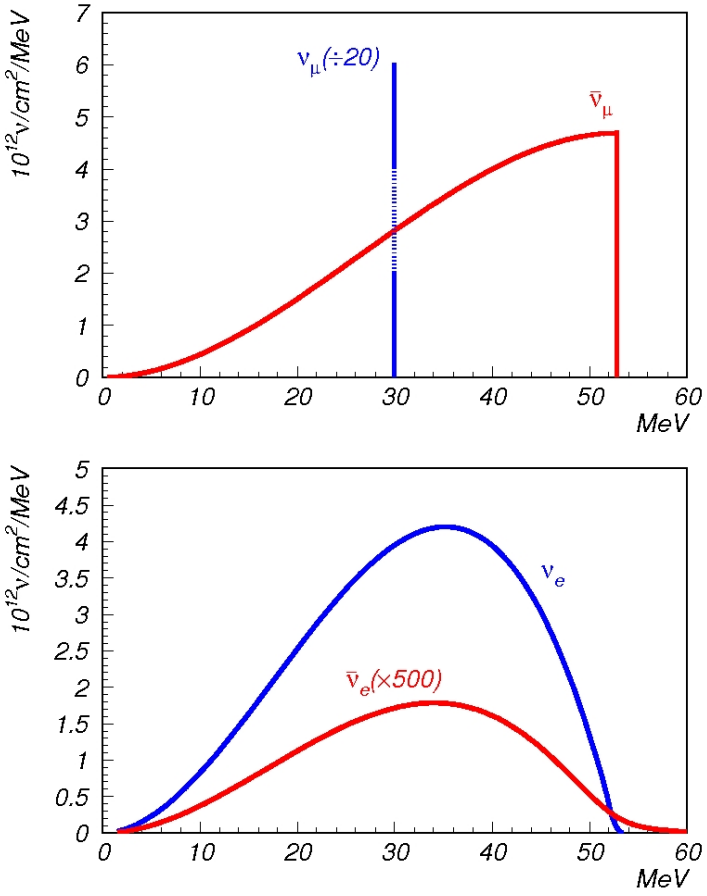
The LSND Experiment

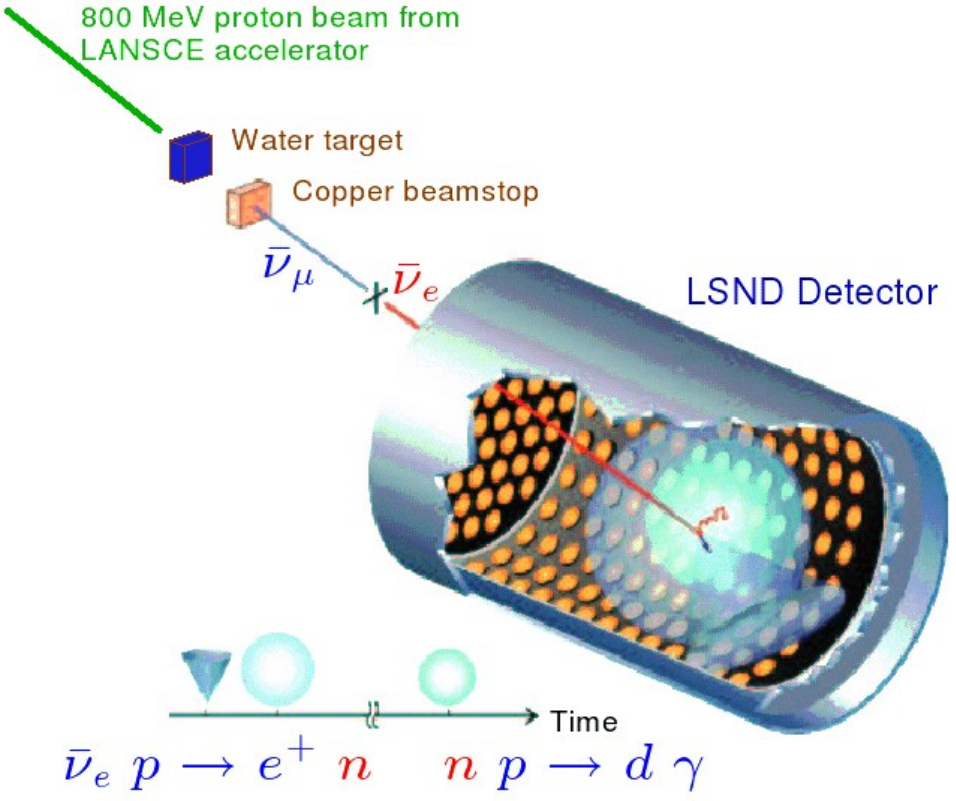
- *The neutrino source:*
  - $\bar{\nu}_\mu$ from: $\pi^+ \to \mu^+ \nu_\mu$, $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
  - $E_\nu = 20 - 53$ MeV, $L_\nu = 25 - 35$ m
  - Almost no $\bar{\nu}_e$ at source

- *The neutrino detector:*

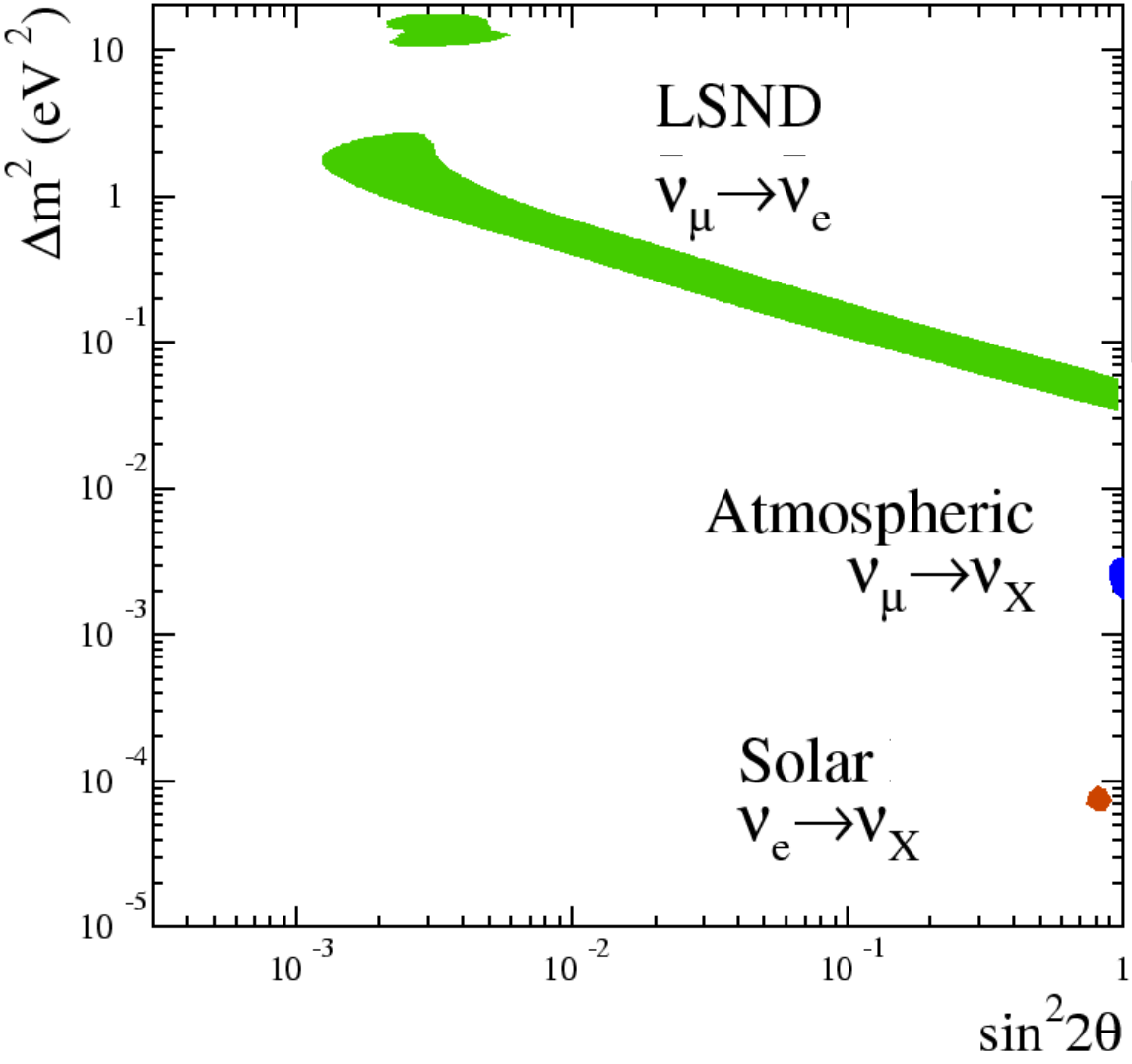
For $\bar{\nu}_e p \to e^+ n$ interactions, detects:

- Cherenkov/scintillation light from e^+
- Scintillation light from n capture





The LSND Oscillation Result



$\overline{\nu_e}$ **candidate excess:**
$(87.9 \pm 22.4 \pm 6.0) \rightarrow 3.8\sigma$

If interpreted as oscillations:
$\langle P(\overline{\nu_\mu} \to \overline{\nu_e}) \rangle = (0.264 \pm 0.067 \pm 0.045)\%$

Mass and mixing parameters:
$\Delta m^2 \sim 0.1\text{–}10\ eV^2$, small mixing
Large $(\sin^2 2\theta, \Delta m^2)$ degeneracy

$\Delta m^2_{\text{LSND}} \gg \Delta m^2_{\text{atm}} + \Delta m^2_{\text{sol}}$ and
$\Delta m^2_{\text{LSND}} \sim 1\ \text{eV}^2$:
Cannot be explained within the standard neutrino physics and cosmology paradigms

Reconciling LSND with Particle Physics and Cosmology

- Two light sterile neutrinos and low-energy seesaws? (hep-ph/0305255, hep-ph/0608147)
- Sterile neutrino and CPT invariance violation? (hep-ph/0308299)
- Sterile neutrino and large extra dimensions? (hep-ph/0504096)
- Heavy sterile neutrino decay? (hep-ph/0505216)
- Mass varying neutrinos? (hep-ph/0509163)
- Lorentz invariance violation? (hep-ph/0606154)
- Quantum decoherence? (hep-ph/0603028)
- Cosmological lepton asymmetry? (hep-ph/9508275, astro-ph/0608206)
- Inflationary models with low reheating temperature? (astro-ph/0403323)
- Extra neutrino couplings to massless bosons? (astro-ph/0404585)
- Non-standard ($w \neq -1$) dark energy equation of state? (astro-ph/0505551)
- ...

Generally requires to give away or introduce something fundamental

MiniBooNE Goal and Design Strategy

- **Primary goal:**

confirm or refute the oscillation interpretation of the LSND anomaly in an unambiguous and independent way

- **Design strategy to accomplish this goal:**
  - High statistics sample of electron neutrino candidate events
  - Keep L/E as LSND, with order-of-magnitude longer baseline (~500 m) and higher neutrino energy (~800 MeV)

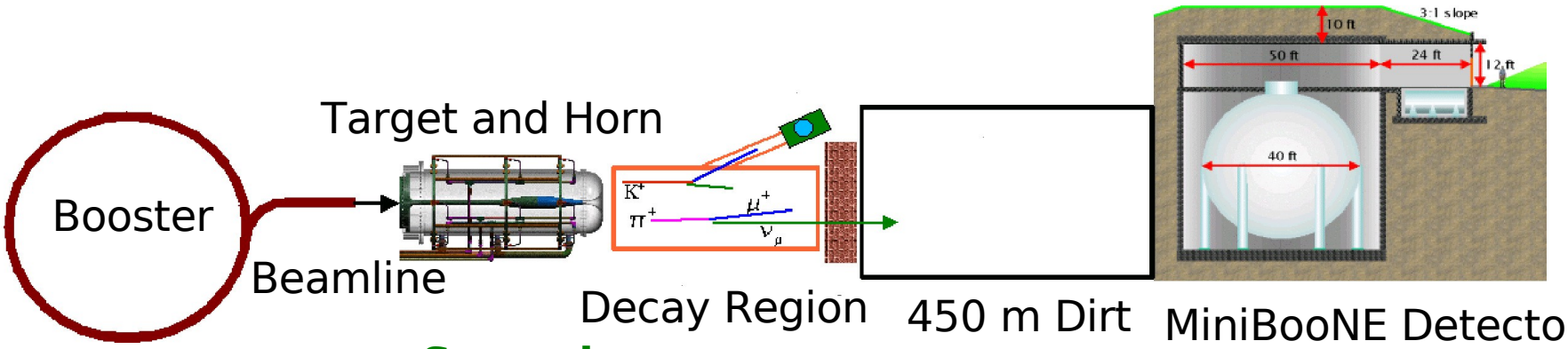
    -> different oscillation signature, backgrounds, systematics

MiniBooNE Collaboration



U. of Alabama
Bucknell U.
U. of Cincinnati
U. of Colorado
Columbia U.
Embry Riddle Aeronautical U.
Fermi National Accelerator Lab.
Indiana U.
Los Alamos National Lab.
Louisiana State U.
U. of Michigan
Princeton U.
Saint Mary's U. of Minnesota
Virginia Polytechnic Inst. & State U.
Western Illinois U.
Yale U.

Neutrino Beam



Primary Beam → **Secondary Beam** → **Neutrino Beam**

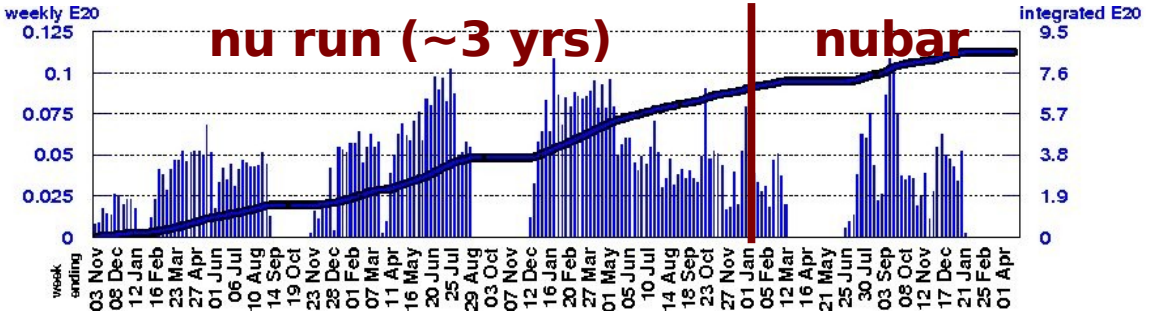
(protons) (mesons)

Primary Beam: 8 GeV protons from Booster, $8 \cdot 10^{-6}$ duty factor

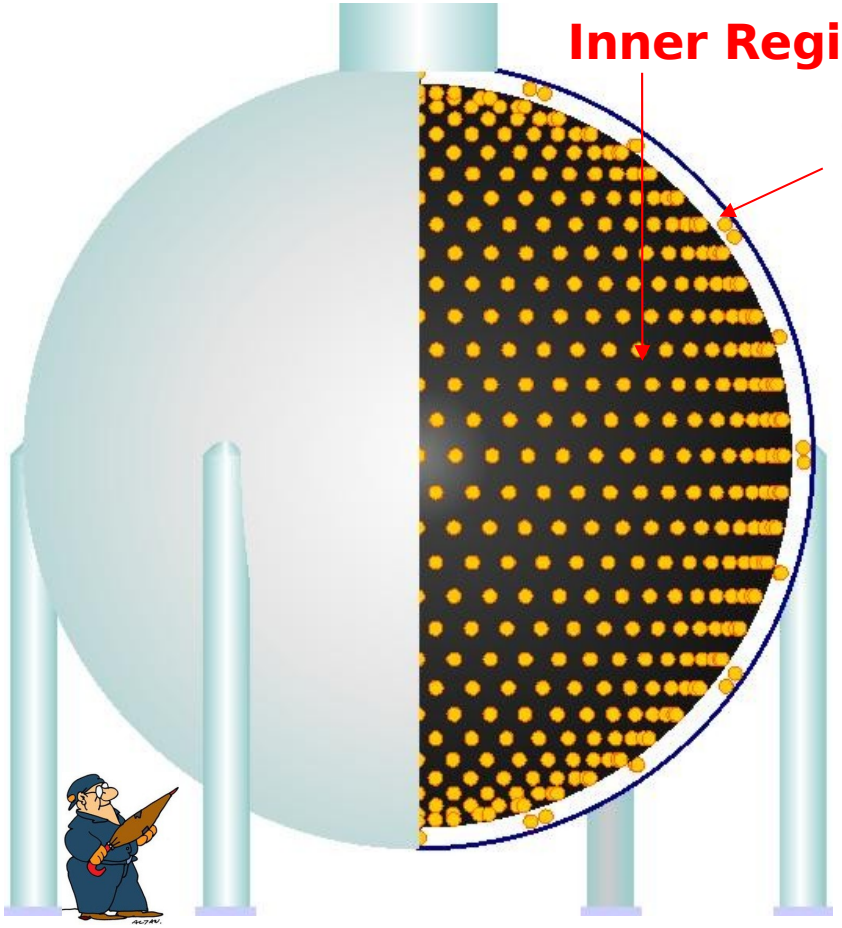
Secondary Beam: mesons are produced from protons striking Be target, and focused by horn. Switchable horn polarity allows for nu and nubar beams

Neutrino Beam: neutrinos from meson decay in 50m pipe, pass through 450m of dirt (and oscillate?) to reach MiniBooNE detector

Number of accumulated protons on target: $8.5 \cdot 10^{20}$
Used in current neutrino oscillation analysis: $5.6 \cdot 10^{20}$

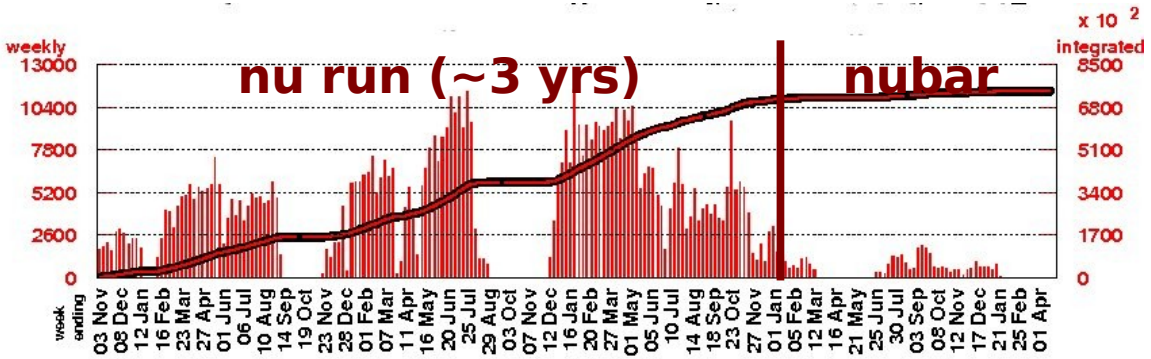


Neutrino Detector



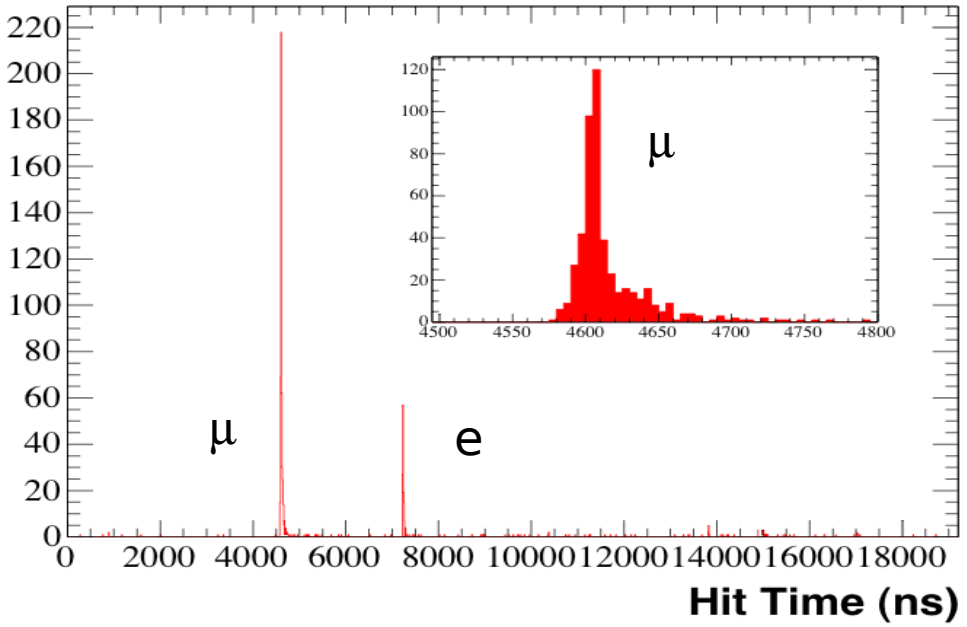
- 12 m in diameter sphere filled with 800 t of undoped mineral oil
- Light tight inner region with 1280, 20 cm diam., PMTs (10% coverage)
- 240 PMTs in veto region (>99.9% veto efficiency)
- Neutrino interactions in oil produce:
  - Prompt, ring-distributed, Cerenkov light
  - Delayed, isotropic, scintillation light
- Light transmission affected by: fluorescence, scattering, absorption (>20m for >400 nm light)

Number of accumulated neutrino interactions: $7.4 \cdot 10^5$

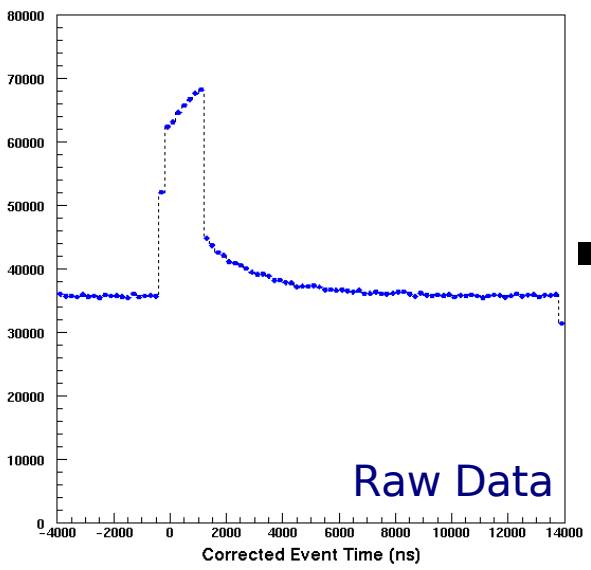


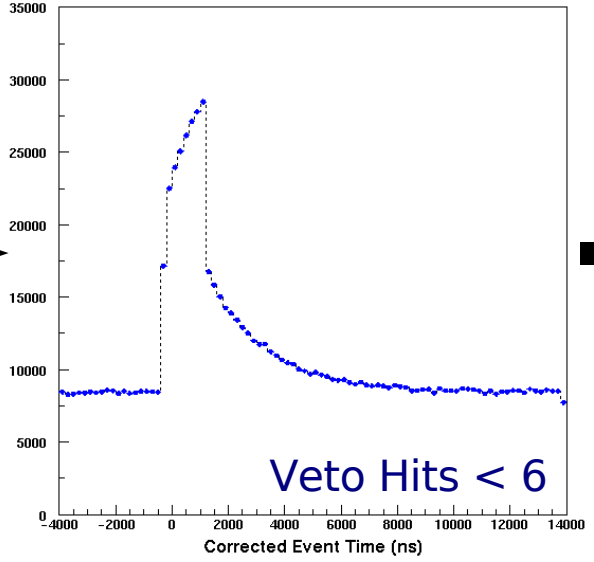
Neutrino Events

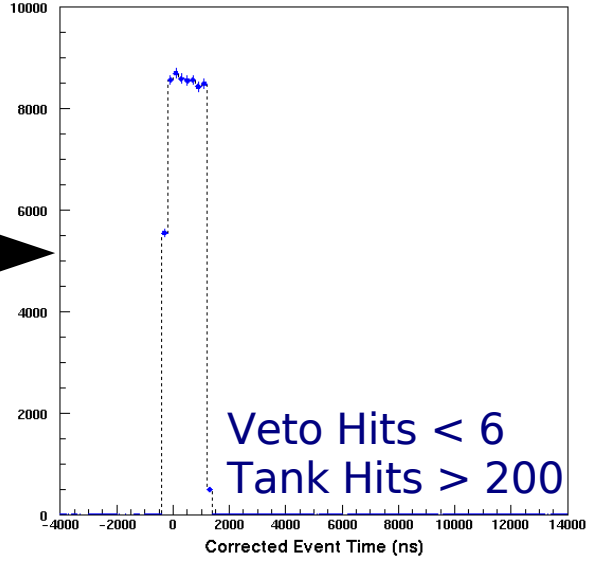
- A 19.2 μs beam trigger window encompasses the 1.6 μs spill
- PMT activity clustered in time form "subevents"
- PMT hits for a muon from a ν_μ charged current interaction, followed by its decay electron



- Progressively introducing hit-level cuts to reject cosmic ray activity and obtain clean neutrino sample (all subevents):







MiniBooNE Appearance Search

- MiniBooNE initial results:

  - A generic search for an electron neutrino excess (or deficit) in a muon neutrino beam
  - An analysis of the data within a two neutrino, muon-to-electron appearance-only neutrino oscillation context, to test this interpretation of the LSND anomaly

- Two largely independent analyses were performed:

  - Track-based analysis (TBA)
  - Boosted decision tree (BDT) analysis

- Will mostly discuss TBA, chosen as the primary analysis because of slightly better muon-to-electron neutrino appearance sensitivity

- This was a blind analysis. The closed box was opened on March 26, 2007. Results released to the public on April 11, 2007.

Two Analyses

Similarities:

- Same predictions for neutrino fluxes, neutrino interactions, detector response
- Same systematic uncertainty assumptions
- Similar philosophy in constraining backgrounds with MiniBooNE data

Differences:

- Different algorithms for event/track reconstruction and particle identification

Complementary merits:

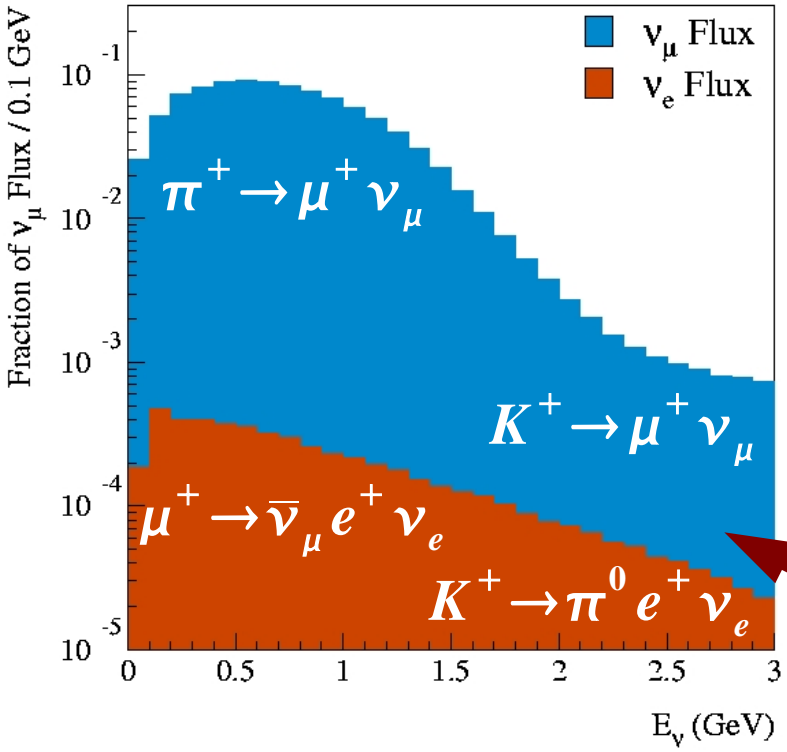
- Track-based analysis (TBA): less sensitive to detector response systematic uncertainties
- Boosted decision tree (BDT) analysis: better oscillation signal – to – background ratio expectation

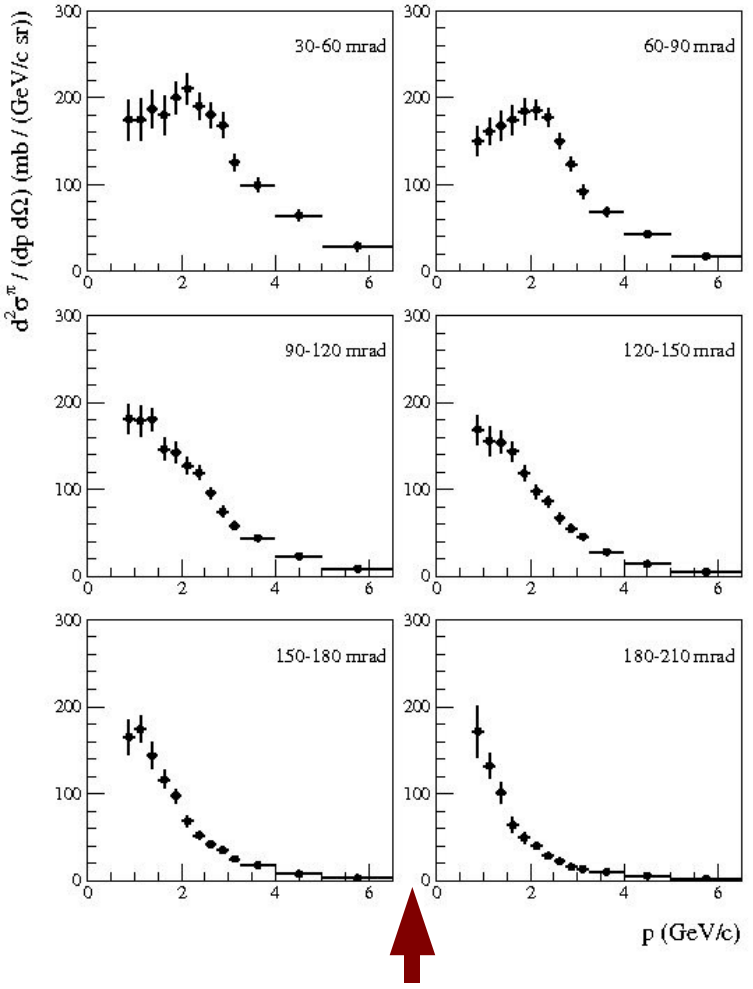
Neutrino Fluxes

GEANT4 beamline description, simulating:

- Primary protons, geometry, materials and horn field
- Interactions, focusing, meson and muon decays

- Pion/kaon production data on beryllium is the most important external physics input to the simulation
-> parametrized according to relevant hadron production data sets



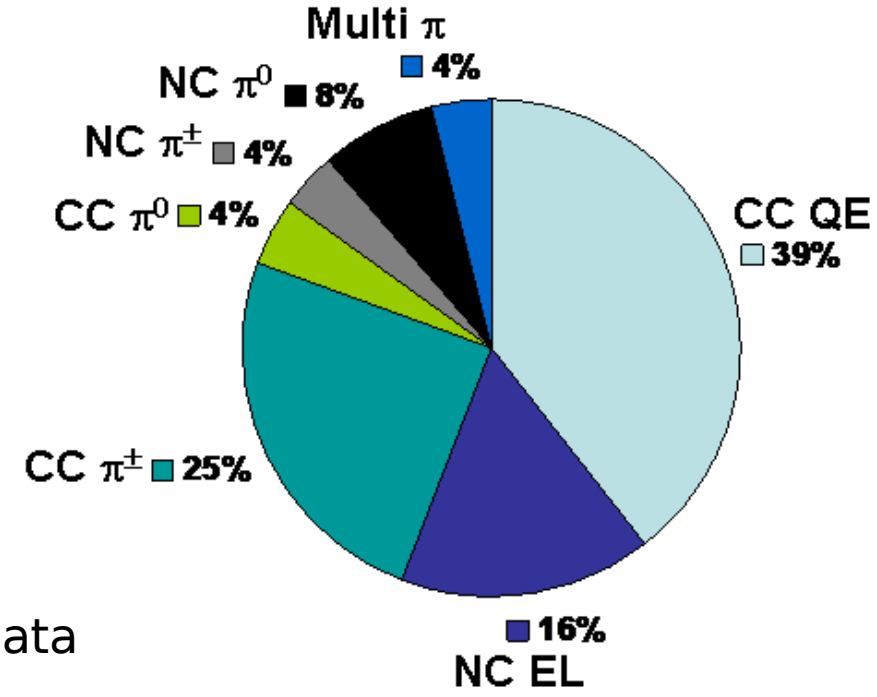


HARP data on:
p(8.9 GeV/c) + Be $\to \pi^+$ + X
(hep-ex/0702024)

ν_μ and ν_e flux predictions. $\nu_e/\nu_\mu \sim 0.5\,\%$

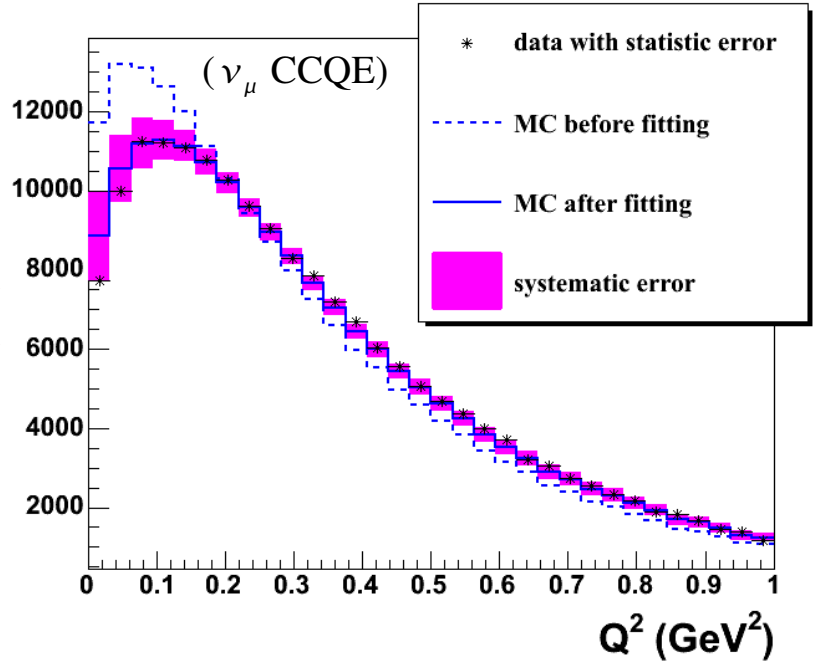
Neutrino Interactions

- **NUANCEv3 cross-section generator**, simulating all relevant neutrino processes, including detailed treatment of Carbon nuclear effects (D. Casper, hep-ph/0208030)



- **External constraints used in NUANCEv3:**
  - Free nucleon cross-sections from neutrino data
  - Nuclear model from electron data
  - Final state interactions from π/p scattering data

- **MiniBooNE's modifications to NUANCEv3 (based on MB neutrino data):**
  - nucleon axial form factor for QE scattering
  - Pauli blocking model
  - coherent pion cross-sections
  - final state interactions
  - angular correlations in resonance decay
  - nuclear de-excitation photon emission



Detector Response

Tabletop measurements & laser calibration

First calibration with michels

Calibration of scintillation light with NC events

Final calibration with michels

Validation with cosmic muons, ν_μ events, and NuMI ν_e events

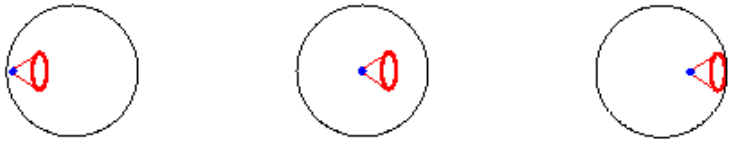
GEANT3 description, with detailed simulation of:

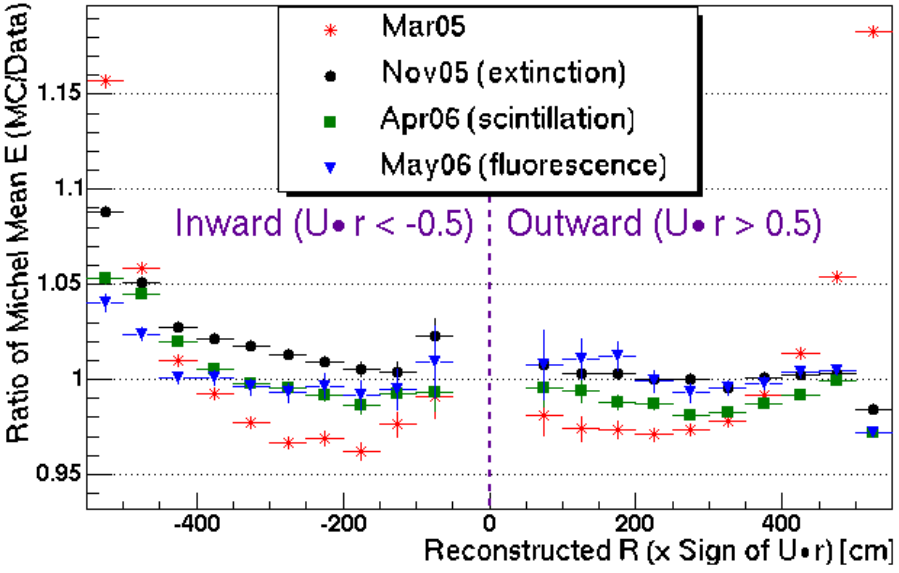
Light production and transmission:

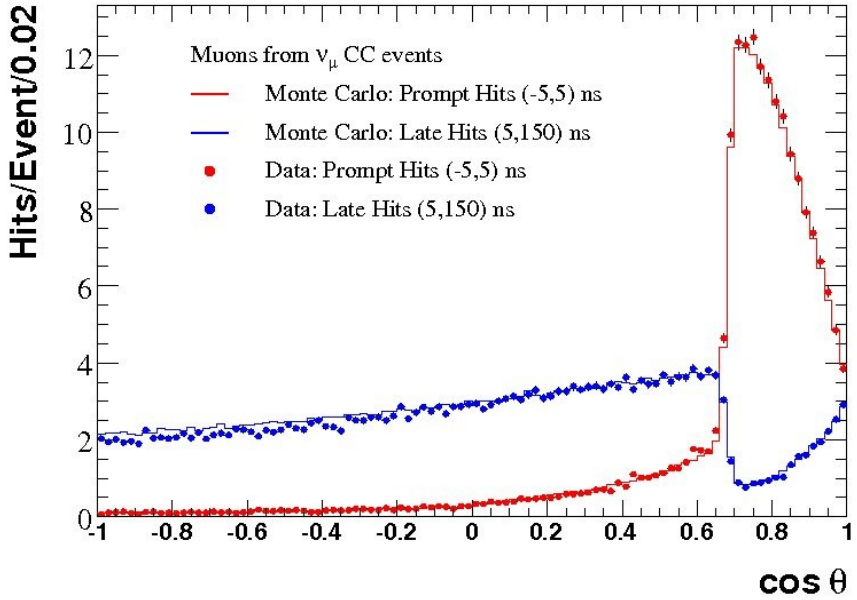
- Cherenkov, scintillation, fluorescence
- tank reflections, Raman/Rayleigh scattering, absorption

PMT charge/time response:

- single PE charge distribution and charge linearity
- time distribution





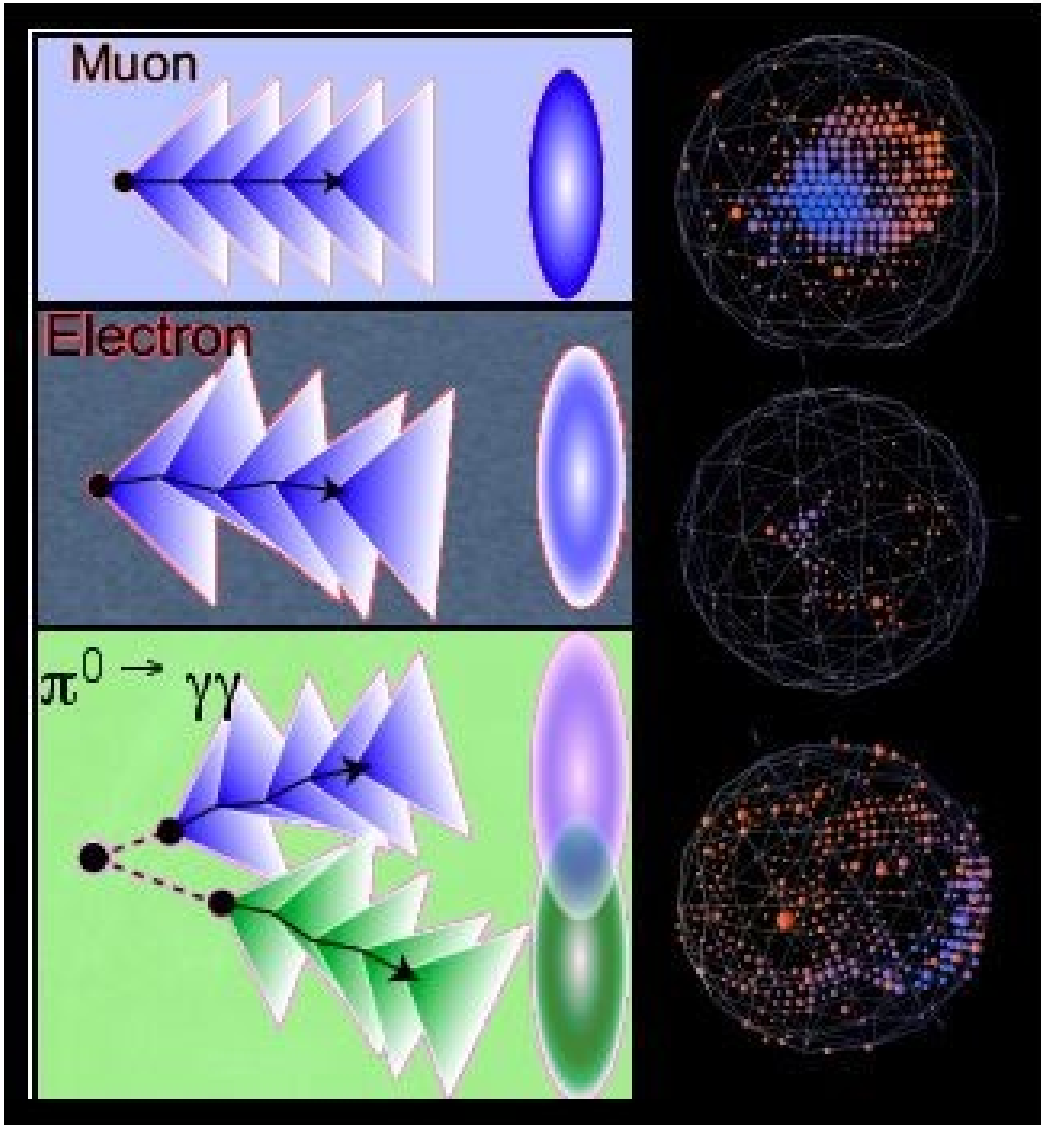


Particles to Identify in Appearance Search

Muons (background):
- long tracks
- sharp Cherenkov ring
- ~80% with decay electron tag

Electrons (signal and intrinsic background):
- short tracks
- fuzzy Cherenkov ring
- single subevent

π^0 -> $\gamma\gamma$ decays (background):
- disconnected short tracks
- typically two fuzzy Cherenkov rings
- single subevent



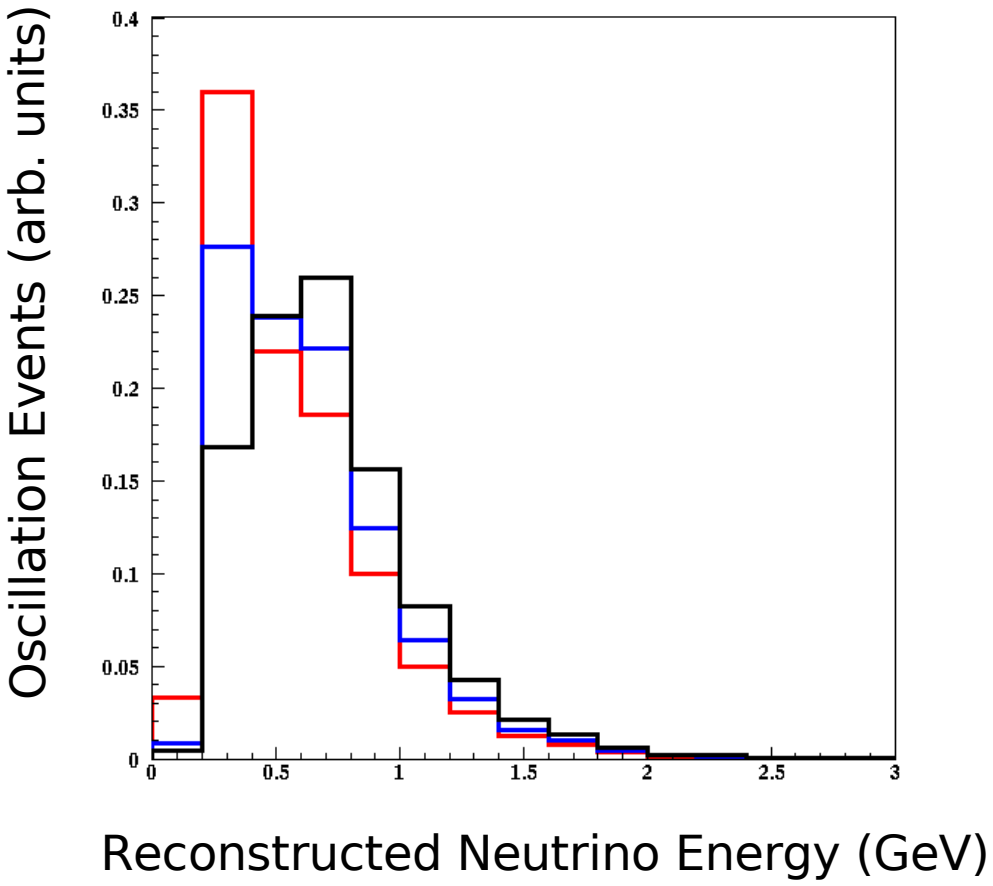
Signal Energy Region in Appearance Search

- Energy range for expected signal events is approximately:

300 < E_ν < 1500 MeV

- MiniBooNE signal examples:

Δm^2=0.4 eV^2
Δm^2=0.7 eV^2
Δm^2=1.0 eV^2



- In this energy range, one can then either:
  - look for a total electron candidate excess (*"counting experiment"*)
  - look for energy-dependence of excess (*"energy fit"*)

Reconstruction and Particle Identification

Reconstruction:

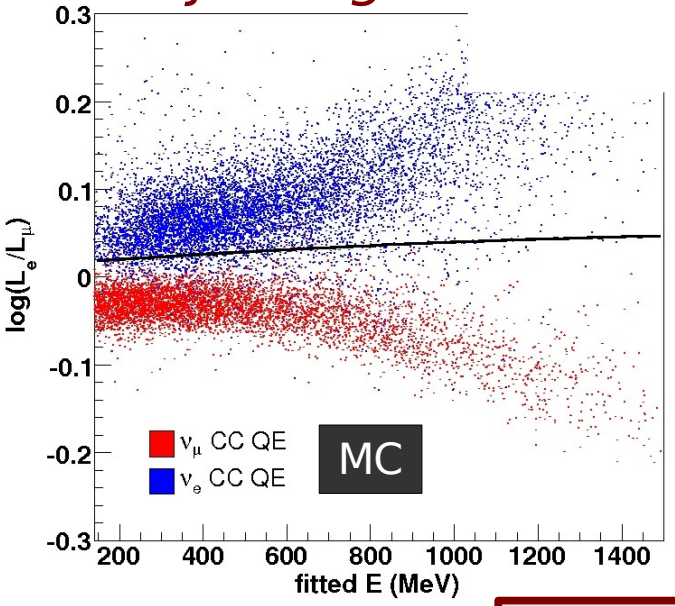
- Detailed model of extended-track light production and propagation

- 22 cm resolution for ν_e event vertex
- 2.8 deg for electron track direction
- 11% for electron track energy
- 20 MeV for invariant mass resolution in NC π^0 events

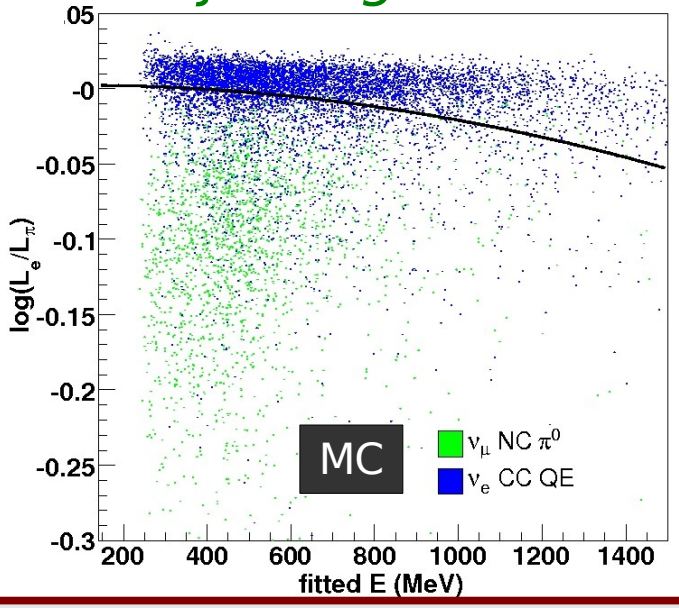
Particle Identification:

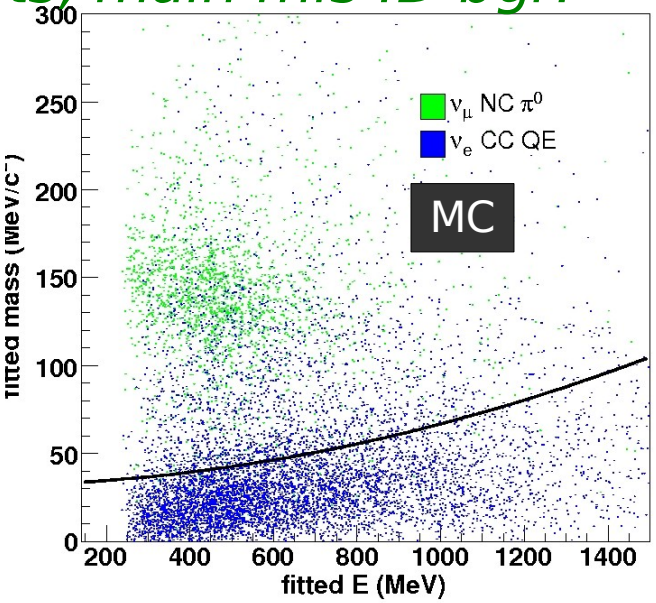
- To reject muons and π^0's, and enhance CCQE fraction in ν_e sample
- Each event reconstructed under muon 1-ring, electron 1-ring, fixed-mass 2-ring, and unconstrained 2-ring hypotheses
- Cut on likelihood fit ratios and 2-ring mass value

Rejecting muons:



Rejecting NC π^0 events, main mis-ID bgr:



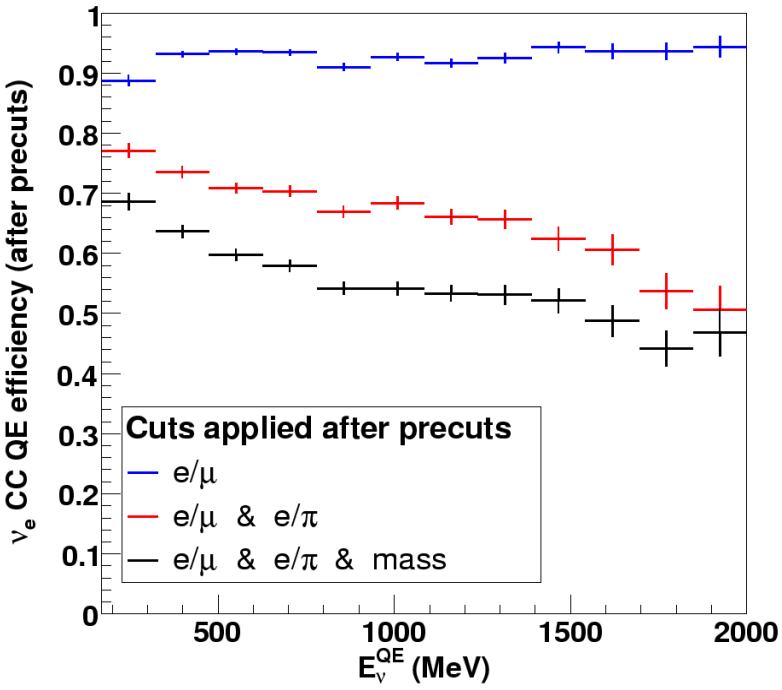


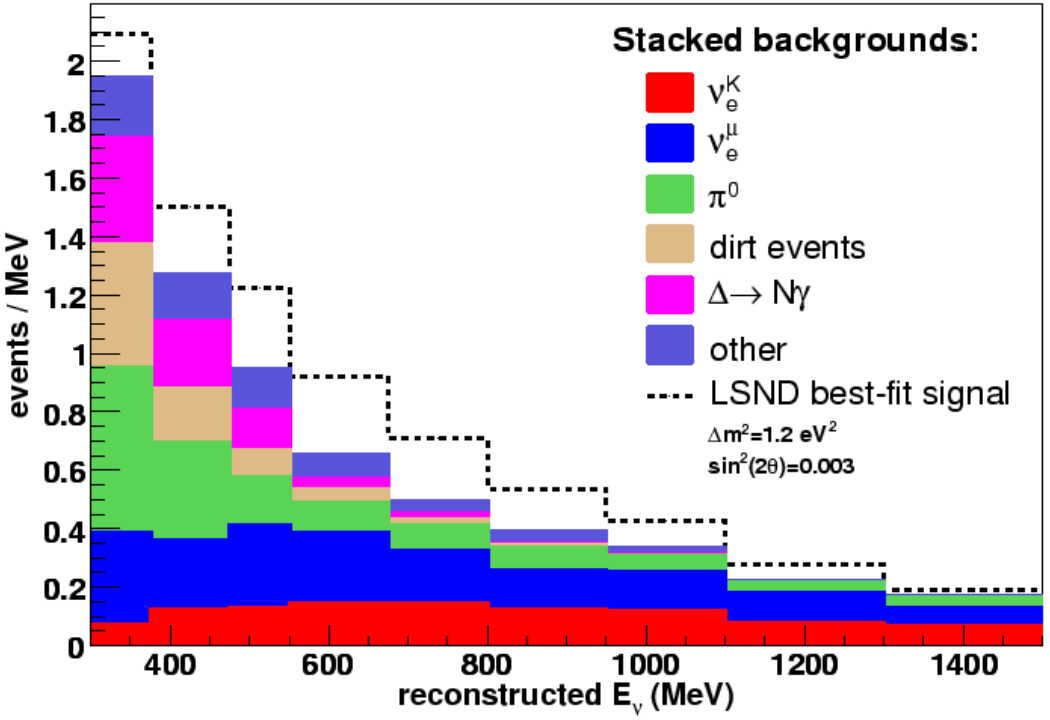
Cut values chosen to optimize $\nu_\mu \rightarrow \nu_e$ sensitivity

Signal Efficiency and Background Composition

- Signal efficiency:

Single subevent,hit-level,
fiducial volume, energy threshold cuts
+ $\mathrm{Log}(L_e/L_\mu)$
+ $\mathrm{Log}(L_e/L_\pi)$
+ invariant mass cuts





- Background events in signal region can be constrained or checked with other samples:

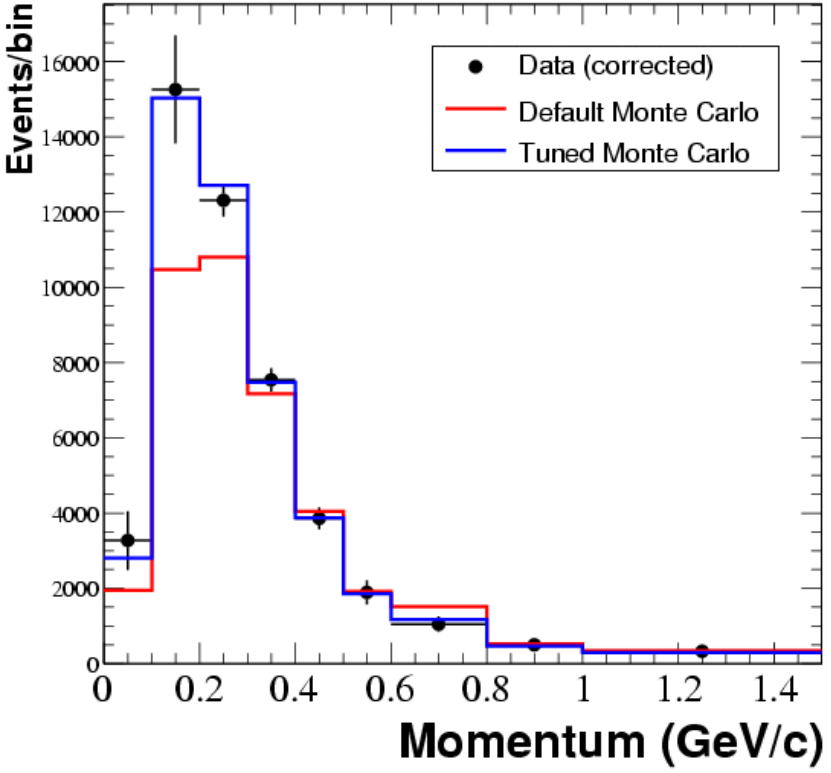
high energy events
ν_μ CC QE
π^0
high radius events
π^0
ν_μ CC QE
ν_μ CC QE

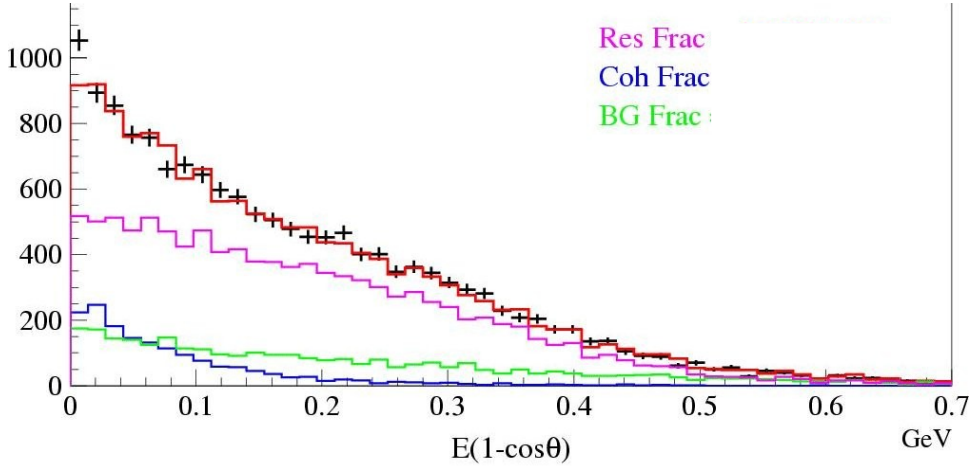
MiniBooNE Constraints on mis-ID Backgrounds

All of the major backgrounds for the ν_e appearance search can be constrained directly from MiniBooNE measurements

NC π^0 background where one photon is not seen:

- Select >90% pure sample of NC π^0 events
- Correct MC π^0 production rate versus π^0 momentum
- Correct MC π^0 mis-ID rate



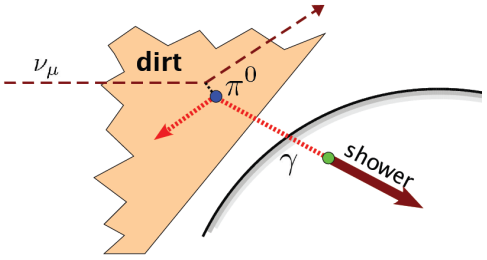


- Ability to isolate resonant/coherent π^0 contributions allows to correct also $\Delta \to N\gamma$ background

MiniBooNE Constraints on mis-ID Backgrounds

All of the major backgrounds for the ν_e appearance search can be constrained directly from MiniBooNE measurements

External backgrounds:



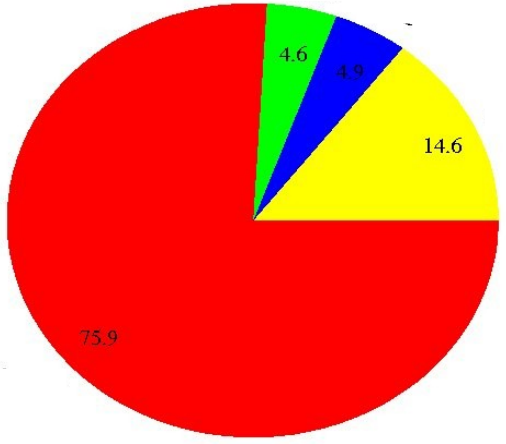
- Neutrino beam interacts with material outside detector creating 100-300 MeV photons that come into the tank unvetoed, producing e-like events

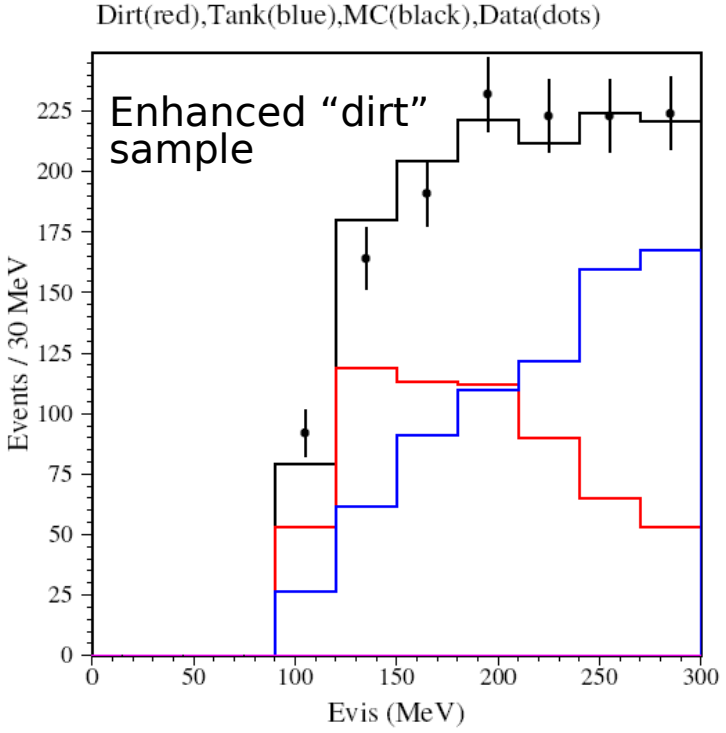
π^0 -> $\gamma\gamma$

CC π^+

CCQE

Other





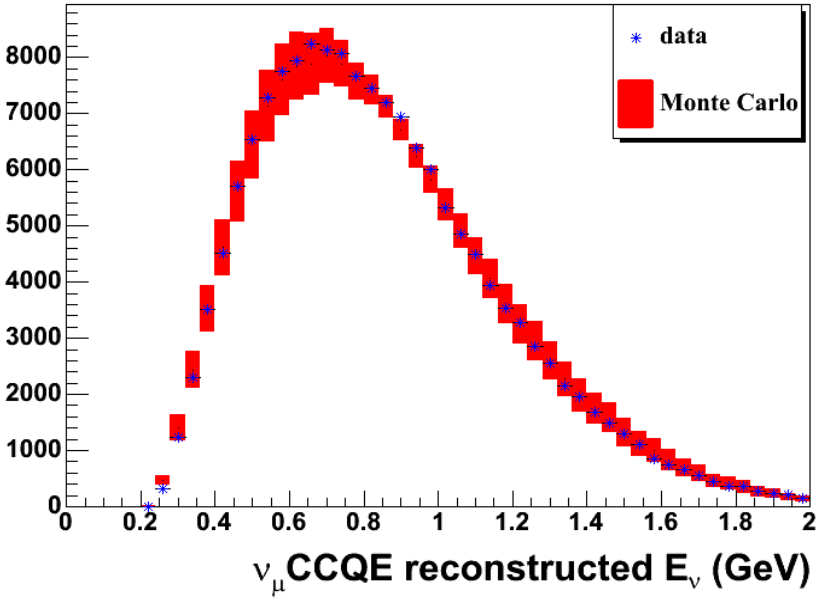
- "Dirt" background rate data/MC = 0.99 ± 0.15

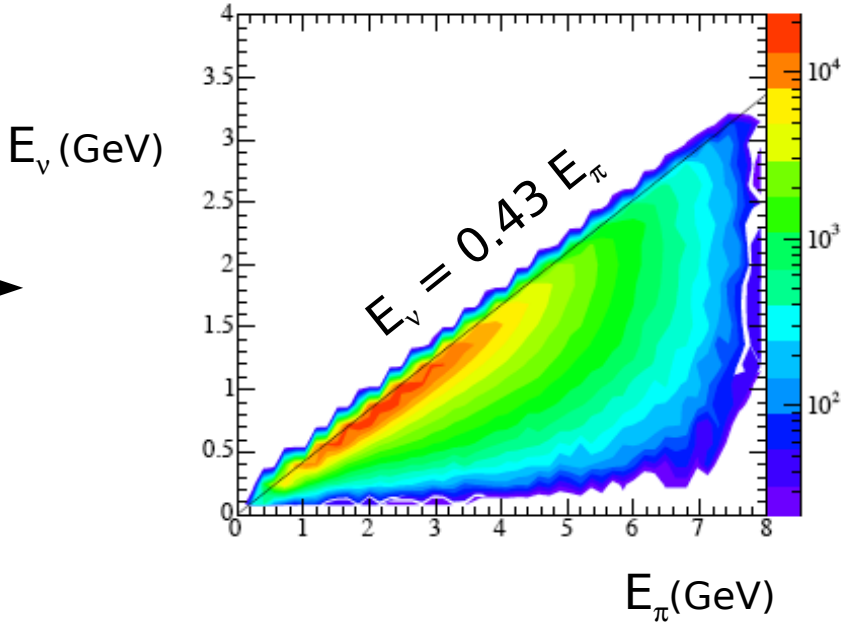
MiniBooNE Constraints on Intrinsic Backgrounds

All of the major backgrounds for the ν_e appearance search can be constrained directly from MiniBooNE measurements

Muon decay ν_e intrinsic background:

- Measure ν_μ flux with ~80% pure ν_μ CCQE sample
- Kinematics allows to infer parent π^+ flux and momentum distribution from observed ν_μ events





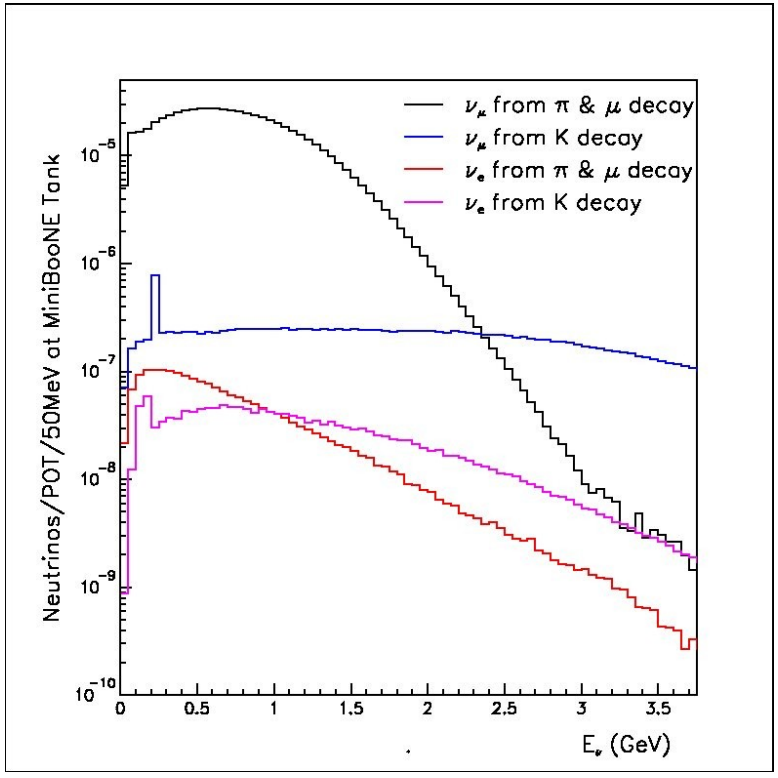
- Once the pion flux is known, the π^+ -> μ^+ -> ν_e decay chain is well constrained
- Use same ν_μ CCQE sample to determine normalization of predicted signal

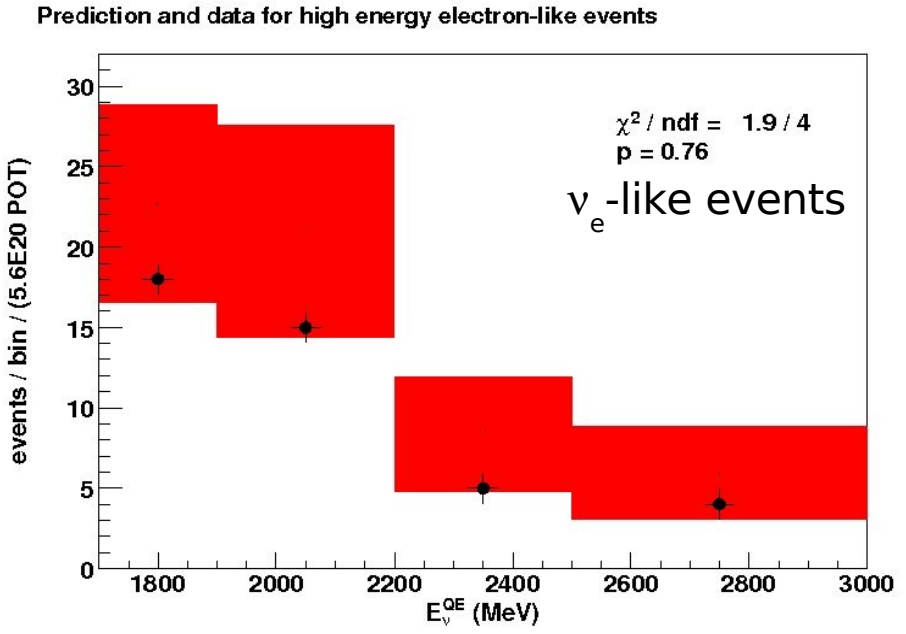
MiniBooNE Constraints on Intrinsic Backgrounds

All of the major backgrounds for the ν_e appearance search can be constrained directly from MiniBooNE measurements

Kaon decay ν_e intrinsic background:

- At high energies, both ν_μ and ν_e-like events are largely due to Kaon decay
- Kaon-induced flux measured at high energies, where no oscillation events are expected, and extrapolated to lower energies





Systematic Uncertainties and Oscillation Sensitivity

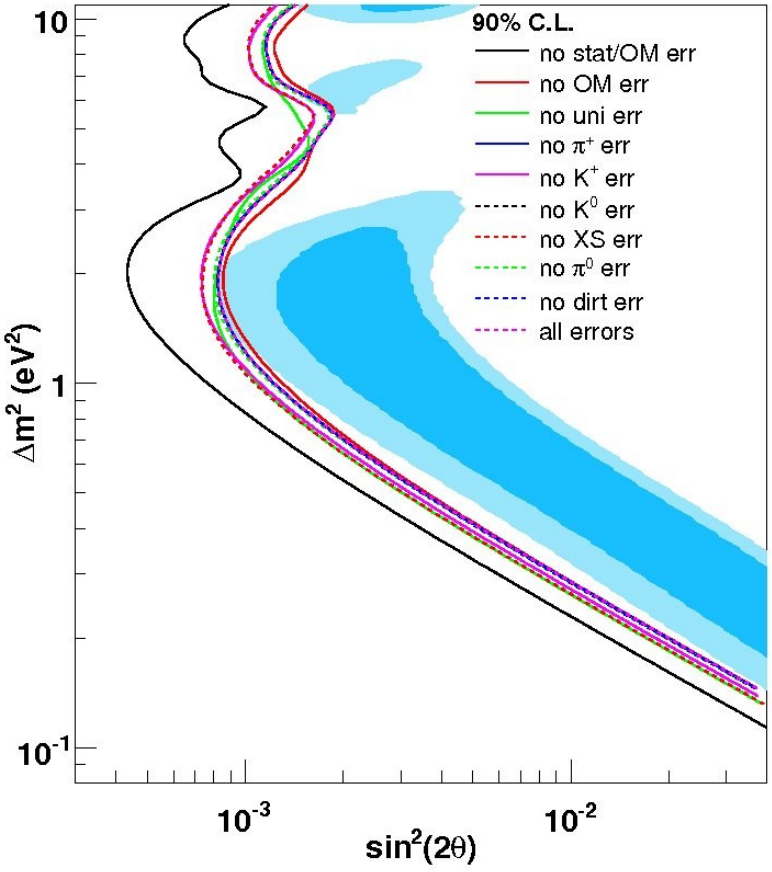
• Systematic uncertainties in predicting electron candidate events come from the modeling of the beam, neutrino interactions, detector

• Start from “first principles” uncertainties from simulation models and measurements external to MiniBooNE. Obtain better uncertainty estimates from MiniBooNE calibration and neutrino data fits

• For primary TBA analysis:

- statistical uncertainty affects sensitivity most
- neutrino cross-section (11 sources), K^+-induced neutrino flux, and final state interactions are most important systematic uncertainties
- detector optical model (OM) systematic uncertainties (~40 parameters varied) have little impact

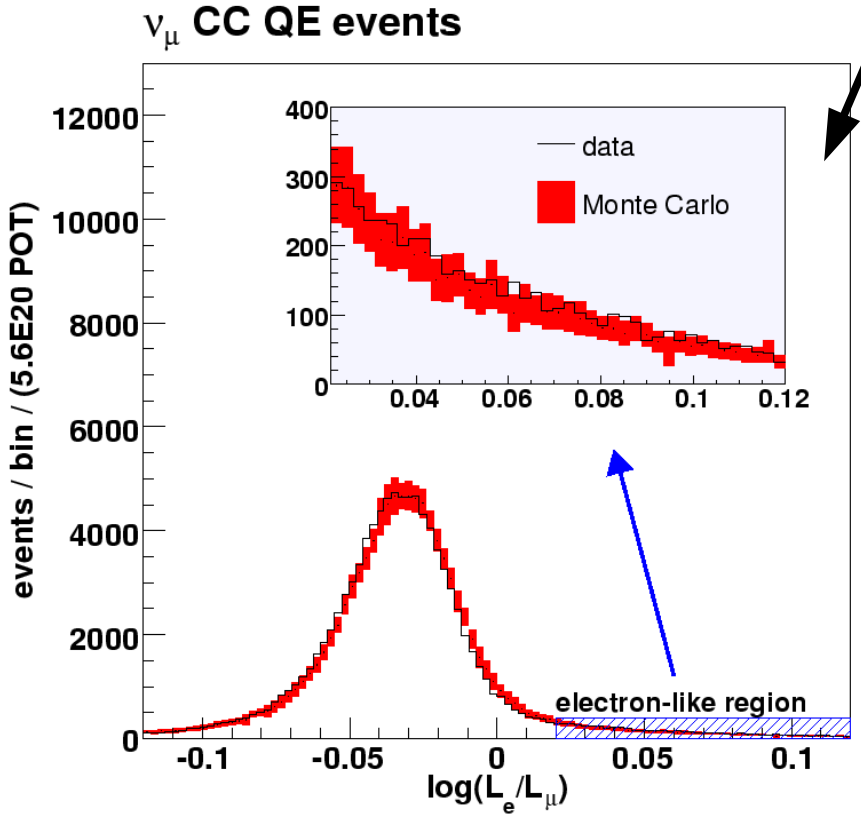
• Complementary (BDT) analysis affected by a different stat./syst. uncertainty mix

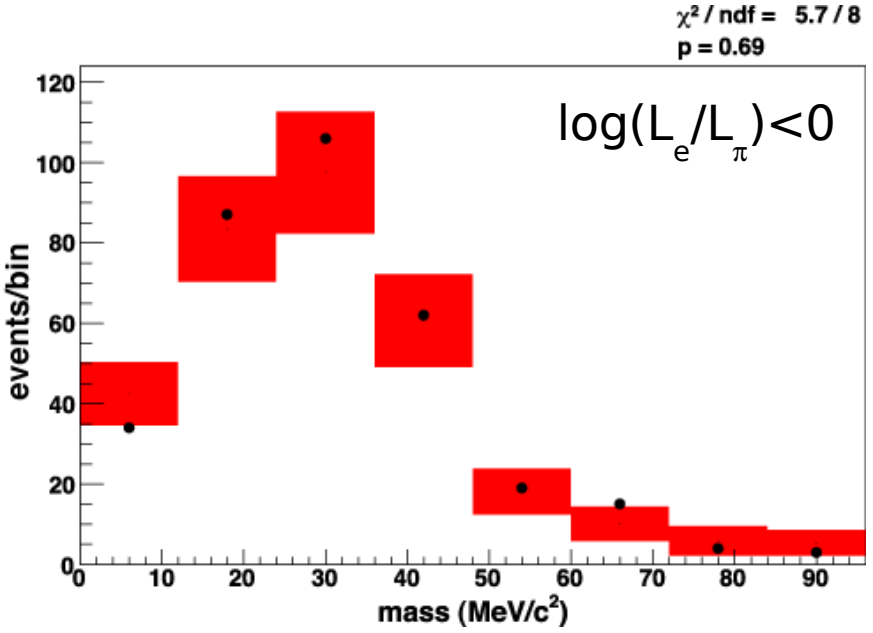


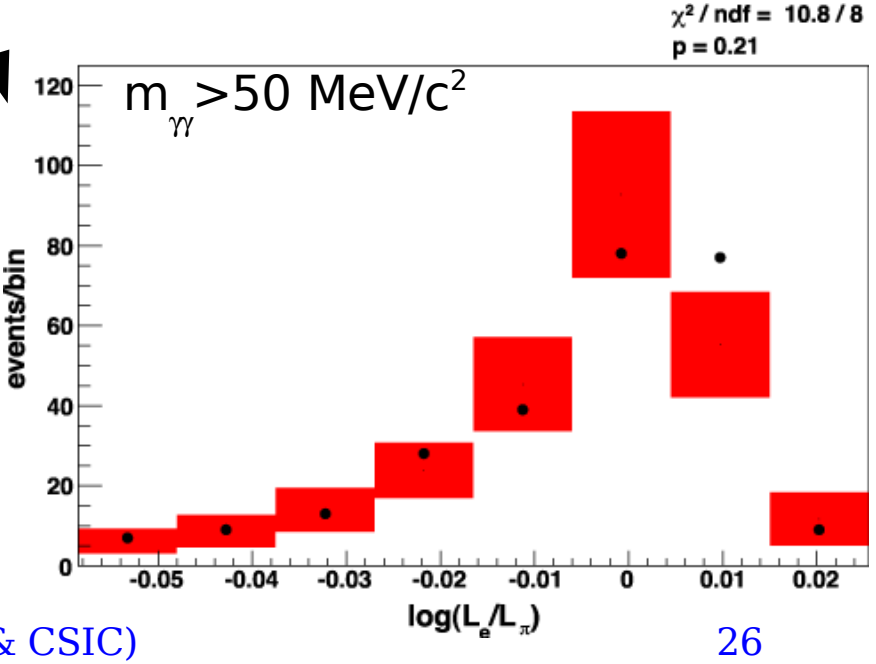
Cross-Checks

- Checked simulation, reconstruction, PID, uncertainty predictions on a variety of open data samples and distributions
- Some examples for ν_e selection quantities
- Good agreement found everywhere

-> proceed to step-wise box opening







Electron Neutrino Box Opening Procedure

Step 1: perform fit of E_ν distribution of electron candidate events in the $300 < E_\nu < 3000$ MeV energy range to oscillation hypothesis, where best-fit oscillation signal added to background prediction is unknown. Disclose χ^2 values from data/MC comparisons of several diagnostic variables

Step 2: disclose histograms for data/MC comparisons of same diagnostic variables

Step 3: disclose χ^2 value for E_ν data/MC comparison over oscillation fit range, still retaining blindness to oscillation signal component

Step 4: disclose full information on electron candidate events and oscillation fit results

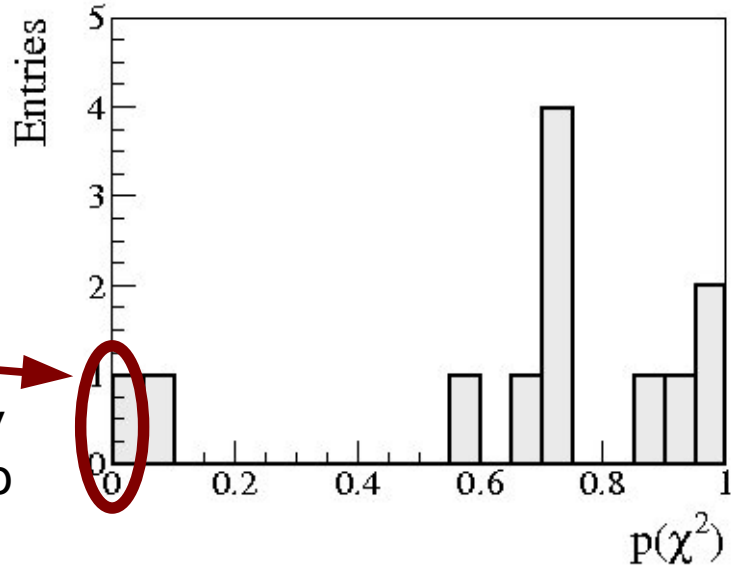
- Progress in a step-wise fashion, with ability to iterate if necessary
- All event selection and oscillation fit procedures are determined before full information on electron candidate events and oscillation fit results is disclosed

Box Opening Step 1: First Try

• X^2 probability for data/MC comparisons on 12 diagnostic variables:

event/track position, direction, visible energy, and PID quantities

• Comparisons looked good except event visible energy: p($X^2 > X^2$(obs)) = 1%



• Indicates poor data/MC agreement beyond ability of 2-neutrino, appearance-only oscillation model to handle

• Triggered further investigations of low-energy background estimates and associated uncertainties, using “sideband” samples
-> we found no evidence of a problem

• However, knowing that:

- backgrounds predicted to rise at low energy
- studies focused suspicions in low-energy region
- choice has negligible impact on oscillation sensitivity

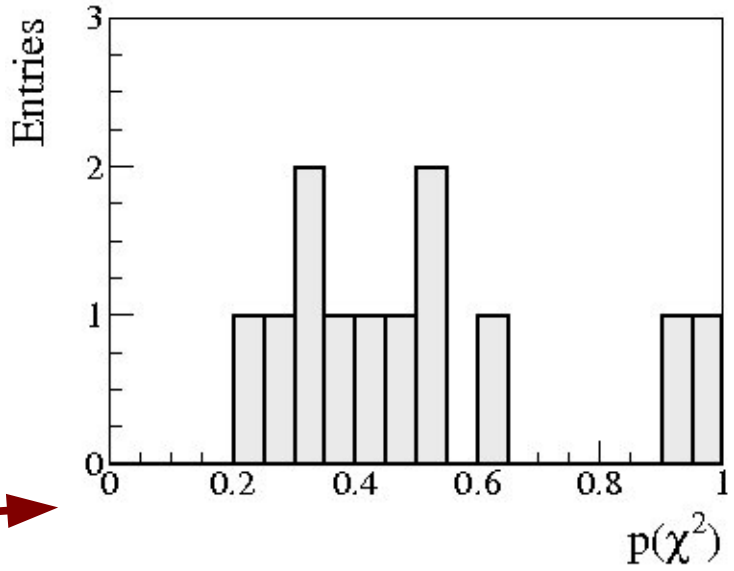
-> we decided to look for oscillations (and diagnostic X^2) in the reduced ($475 < E_\nu < 3000$ MeV) range, and report events over full ($300 < E_\nu < 3000$ MeV) one

Box Opening Steps 1 (Again), 2, and 3

• **Step 1:** χ^2 probability for data/MC comparisons on 12 diagnostic variables:

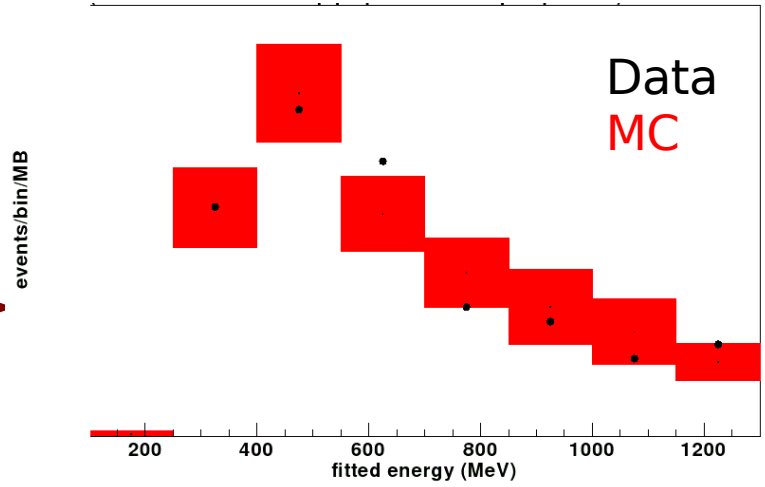
event/track position, direction, visible energy, and PID quantities

• Comparisons look good



• **Step 2:** disclose histograms for data/MC comparisons of same diagnostic variables

• Example: event visible energy data/MC distributions (28% χ^2 probability)



• **Step 3:** disclose χ^2 value for E_ν data/MC comparison over ($475 < E_\nu < 3000$ MeV) oscillation fit range, still retaining blindness to oscillation signal component

• Oscillation best-fit χ^2 probability: 99% (χ^2/dof = 0.9/6)

• *Proceed to full box opening...*


The Box Opening

Oscillation Search Results

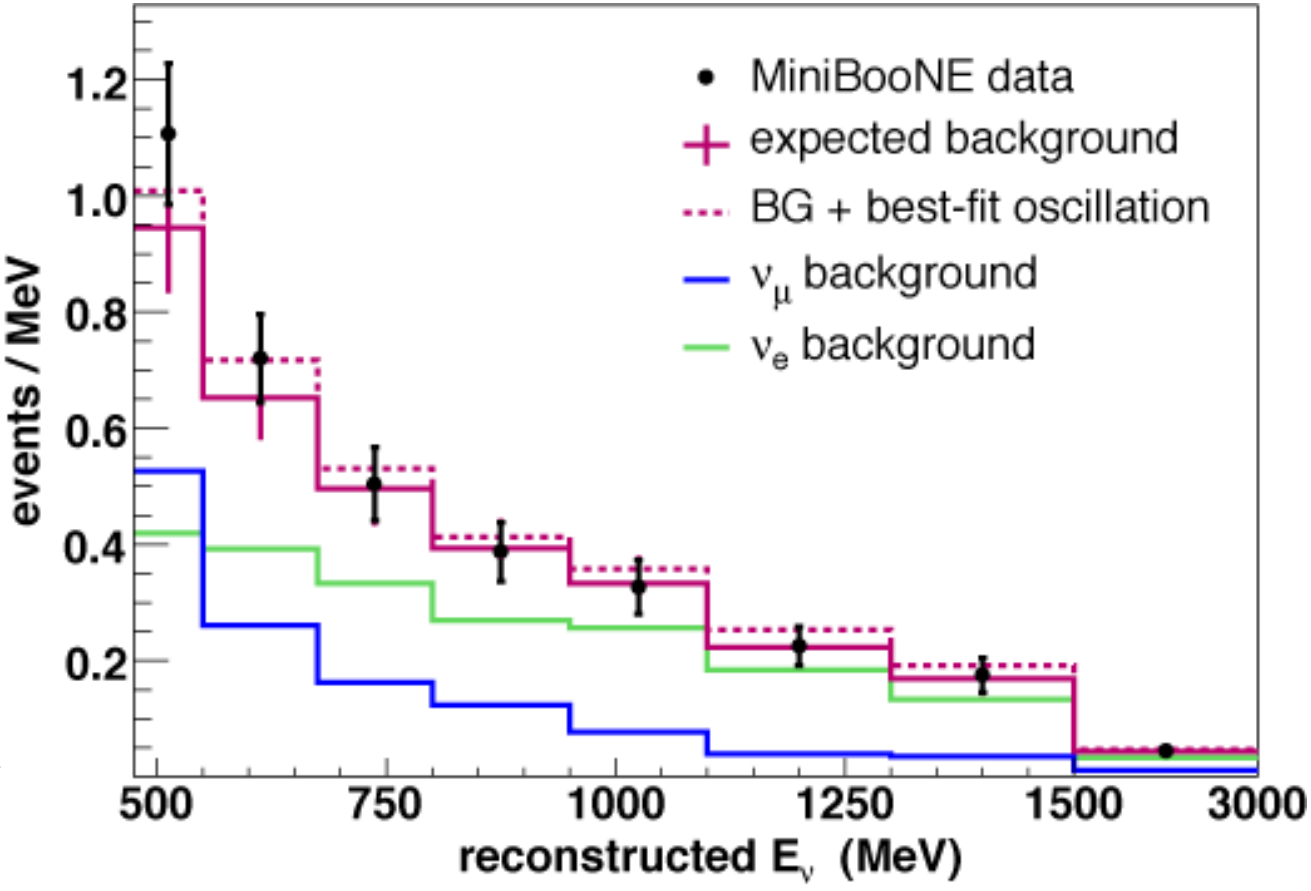
Counting experiment (475-1250 MeV):

- Observe **380 events,** predict **358±19±35 events**
- **0.55 σ** excess over no-oscillations background

No evidence for oscillations

Energy-dependent Oscillation Best-Fit (475-3000 MeV):

- $\sin^2 2\theta = 1.1 \times 10^{-3}$
- $\Delta m^2 = 4.1\ eV^2/c^4$
- $\chi^2_{null} - \chi^2_{best} = 0.94$



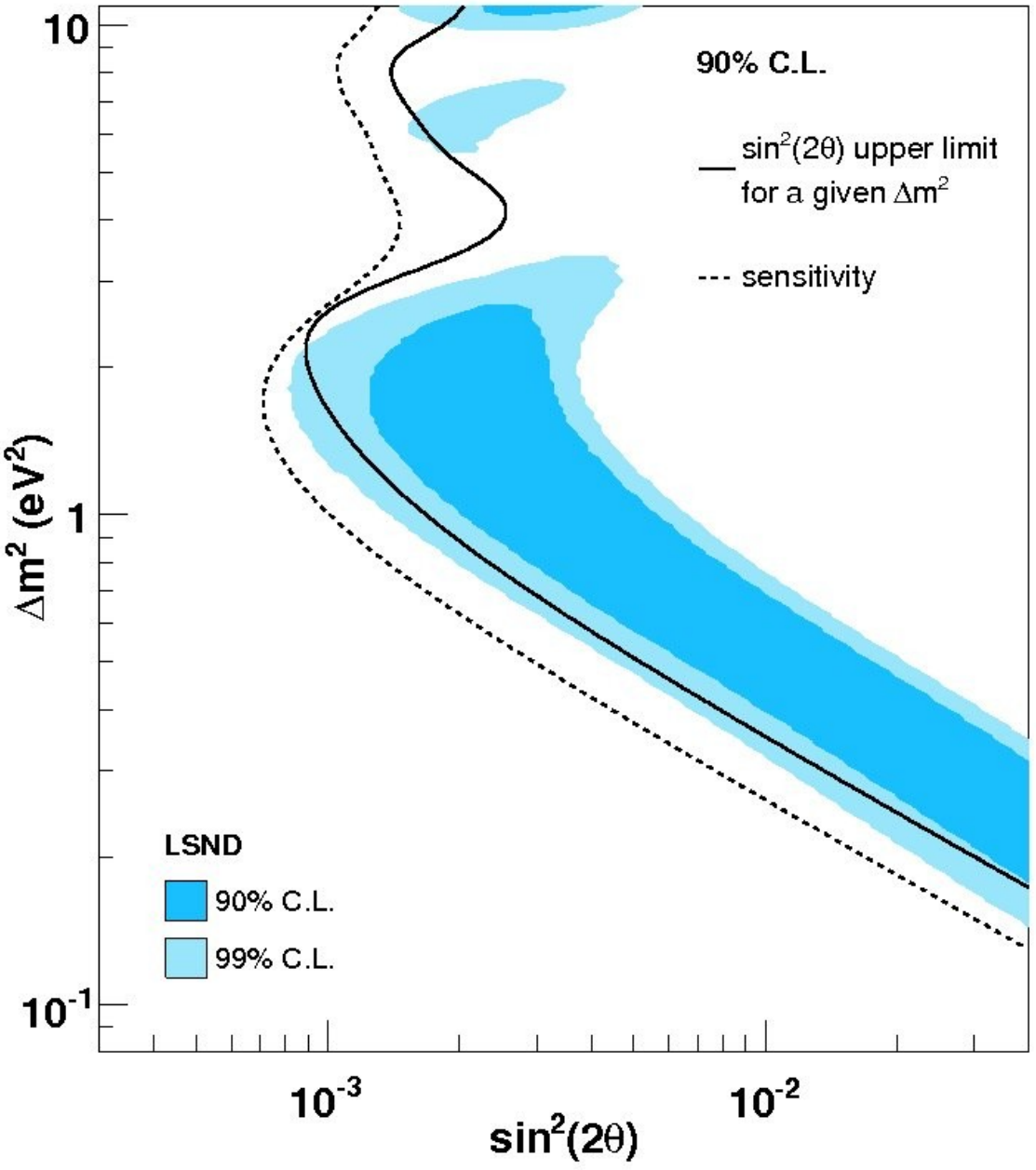
- Data error bars are statistical
- Predictions error bars from diagonal elements of syst.-only covariance matrix

Oscillation Parameters Exclusion

- No overlap in 90% CL allowed LSND and MiniBooNE regions

- MiniBooNE **excludes** two neutrino appearance-only oscillations as the explanation of the LSND anomaly at **~98% CL**

- Any interpetation of the LSND anomaly that would produce a significant excess for E_ν>475 MeV at MiniBooNE is also ruled out



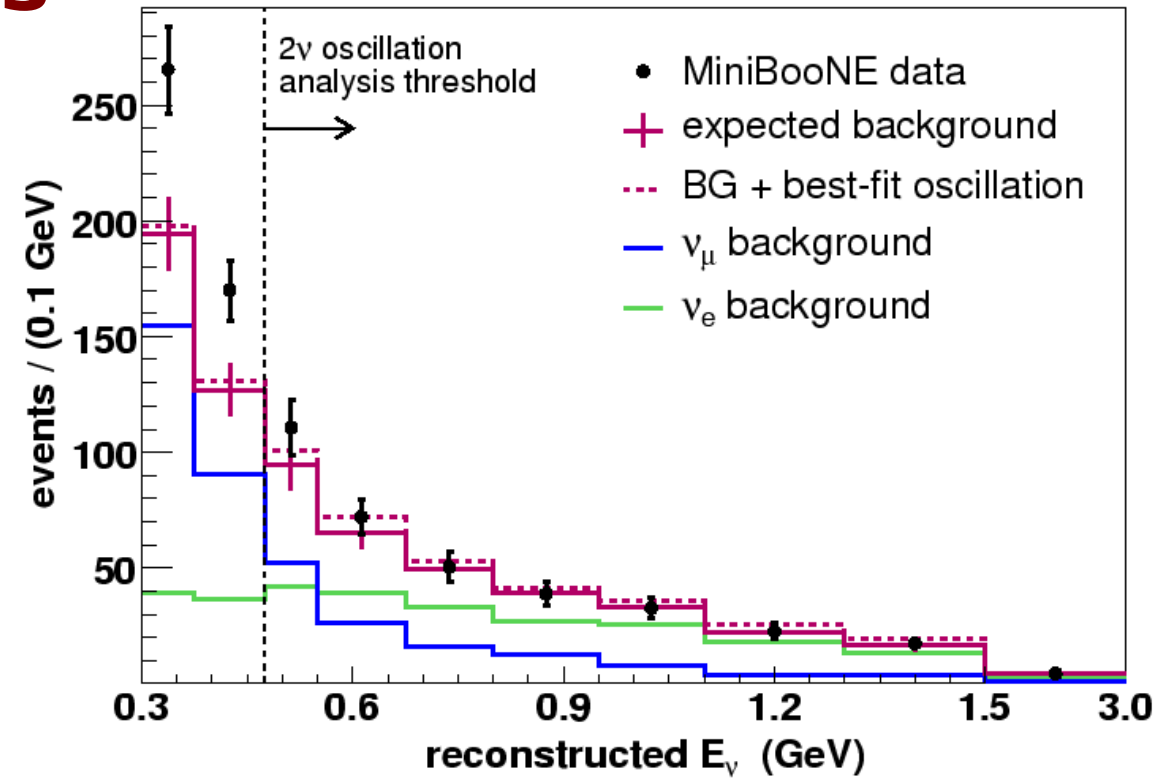
Low-Energy Excess

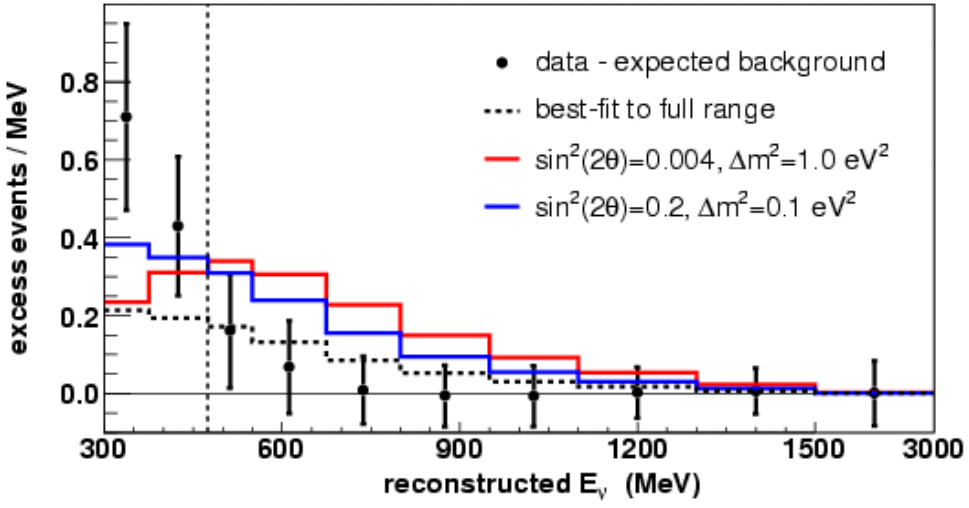
• Electron candidate events over the full (300 < E_ν < 3000 MeV) energy range

• The low-energy data does not match expectations:

3.7σ excess in (300 < E_ν < 475 MeV)

• This discrepancy is *not* understood





• Low-energy excess is *not* consistent with two neutrino appearance oscillations

• Fit to the (300 < E_ν < 3000 MeV) energy range gives a 18% X^2 probability

• Need to do more analysis and gather more facts before making any conclusions

What about independent analysis (BDT)?

Reconstruction and Particle Identification (BDT)

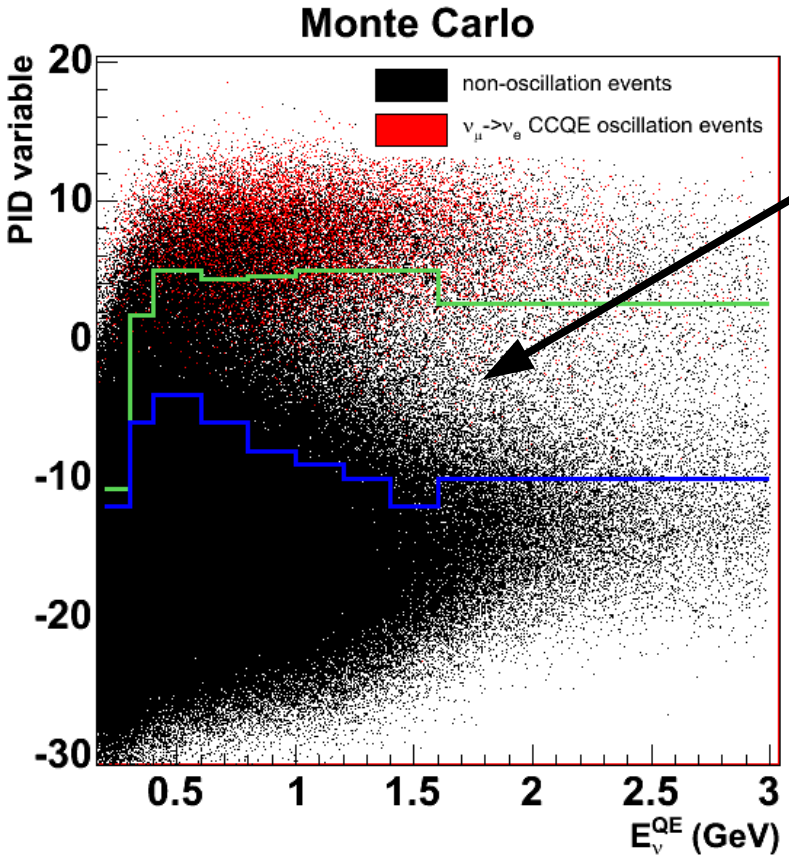
Reconstruction:

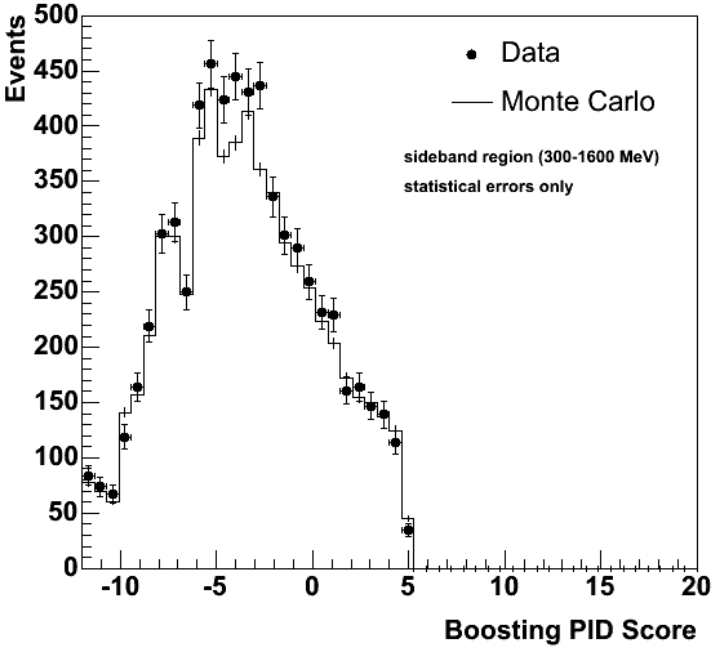
- Slightly less detailed (and performing):

- 24 cm resolution for ν_e event vertex
- 3.4 deg for electron track direction
- 14% for electron track energy

Particle Identification:

- Use sophisticated machine learning technique with 172 PID input variables
- *Boosted decision tree*: "super artificial neural network" combining many weak classifiers into a powerful one
- "Sideband" region in Boosting PID score nearest to oscillation signal, containing mostly ν_μ NC π^0 and ν_μ CCQE events:

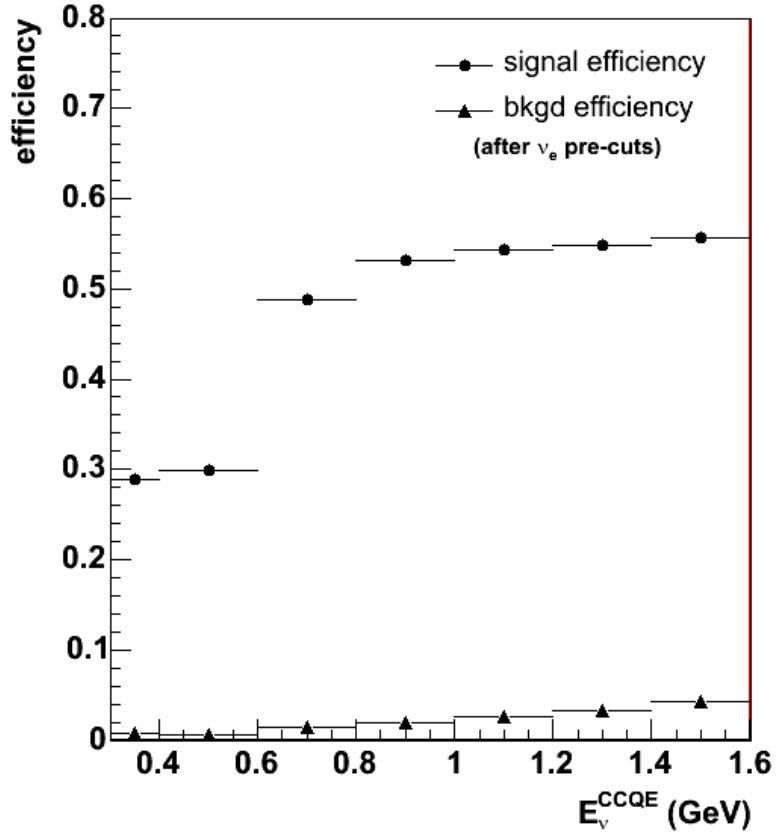


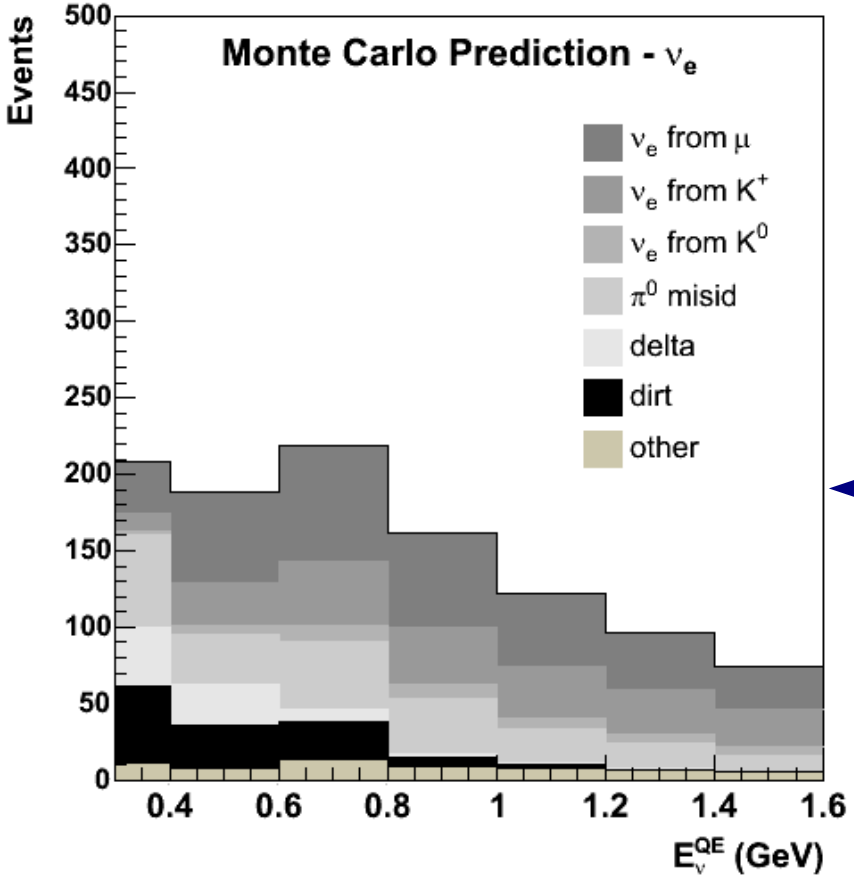


Signal Efficiency and Background Composition (BDT)

- *Signal and background efficiency:*

Single subevent, hit-level, fiducial volume cuts
+ E-dependent Boosting PID score cut

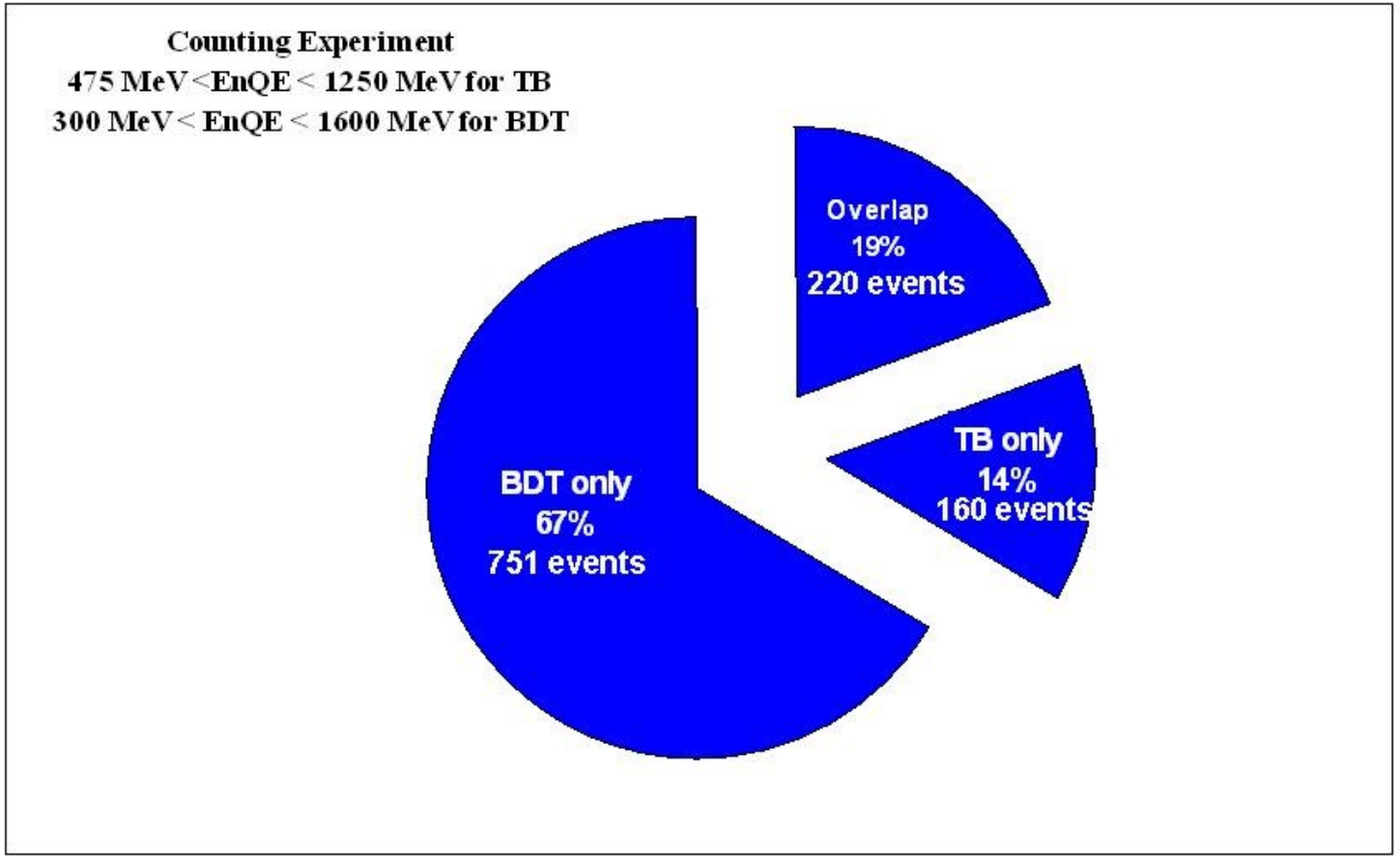




- *Expected background composition in signal region (300-1600 MeV)*
- Background events constrained by:
  - ν_μ events
  - ν_e-like events in low (200-300 MeV) and high (1600-3000 MeV) energy regions, containing negligible oscillation events

Electron Candidate Events in Two Analyses

- Simple and effective way of understanding independence of two analyses is to quantify how independent their ν_e-like data samples are
- Out of all events selected by either one (or both) analyses in respective signal regions, only 19% in common

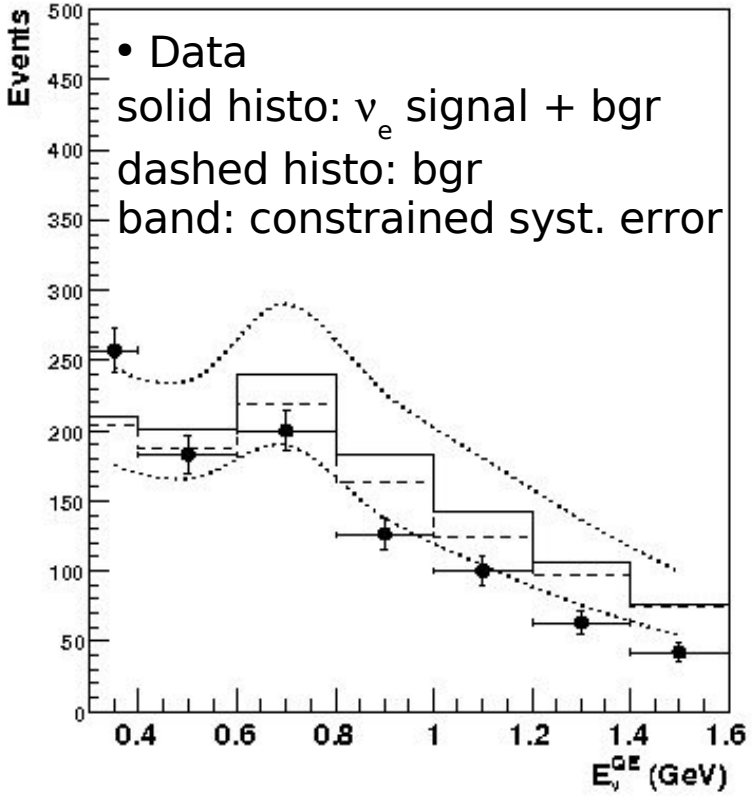


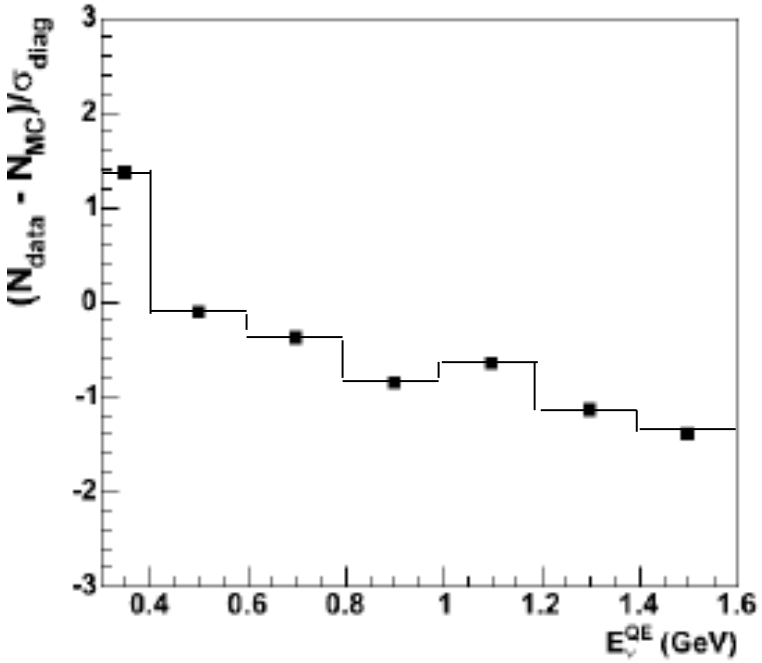
Oscillation Search Results (BDT)

Counting experiment (300-1600 MeV):

- Observe **971 events**
- Predict **1070±33±225 events**
- **-0.38 σ** excess over background

No evidence for oscillations



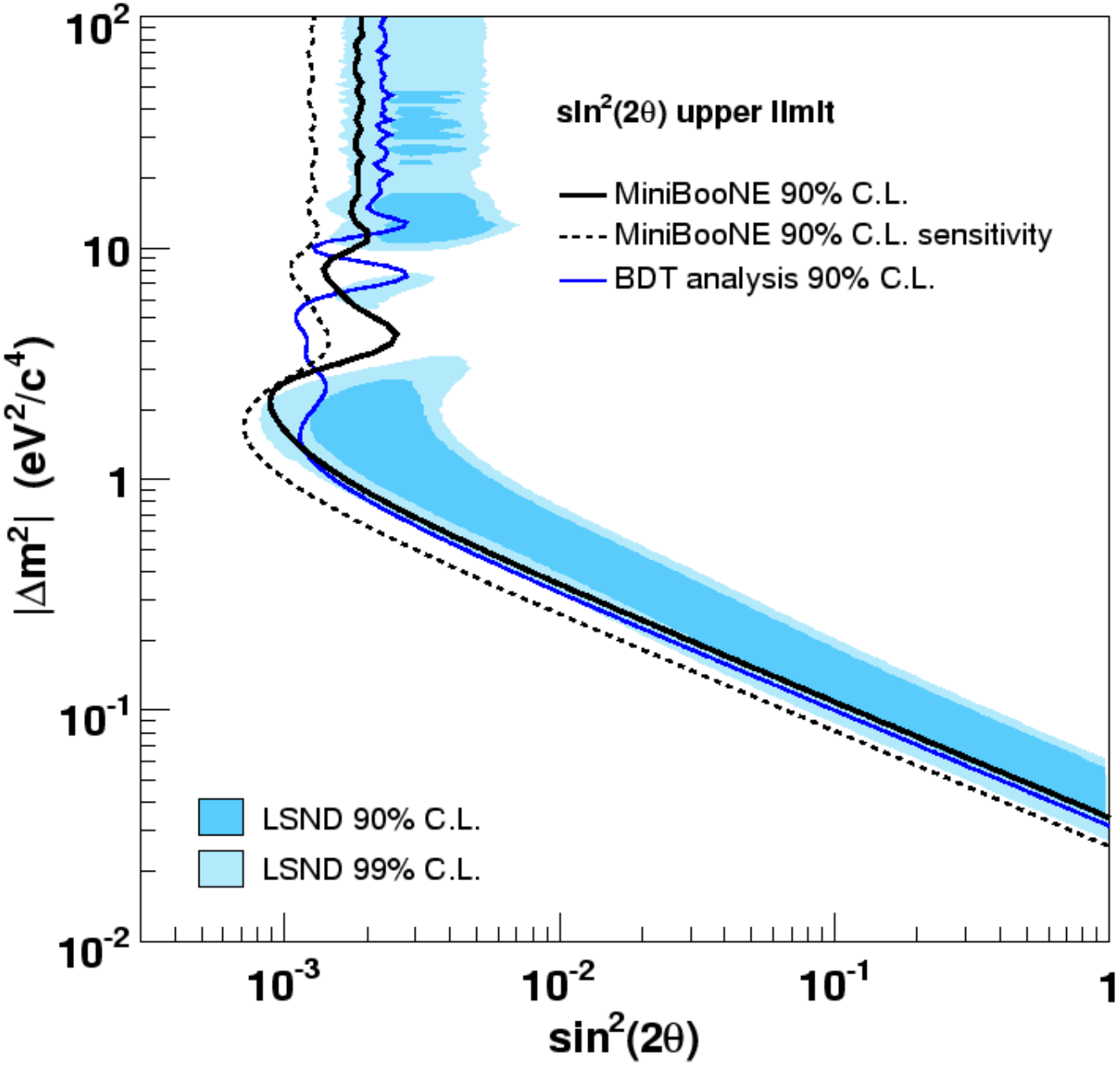


Energy-dependent Oscillation Best-Fit (200-3000 MeV ν_e-like and ν_μ):

- $\sin^2 2\theta = 1.2 \times 10^{-3}$
- $\Delta m^2 = 7.5\ eV^2/c^4$
- $\chi^2_{null} - \chi^2_{best} = 0.71$

- Data error bars are statistical
- Predictions error band from diagonal elements of syst.-only covariance matrix

Oscillation Parameters Exclusion (BDT)



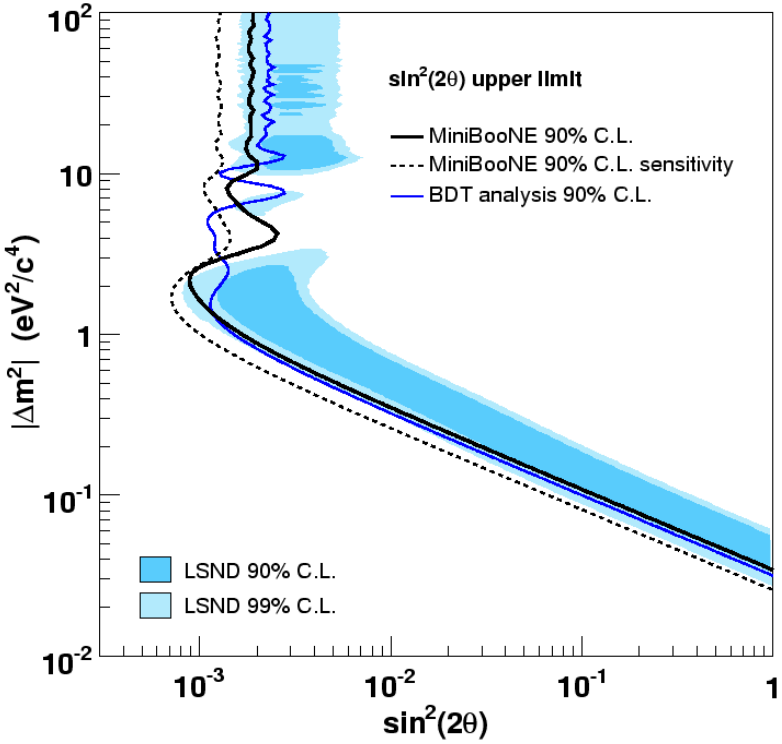
- *Very similar oscillation fit results obtained with two analyses*

Conclusions

The LSND anomaly remains … an anomaly:

- MiniBooNE finds excellent agreement between data and the no-oscillation prediction in the oscillation analysis region

- MiniBooNE excludes at ~98% confidence level the interpretation of the LSND anomaly put forward by the LSND collaboration to interpret its own result:



two neutrino, muon-to-electron neutrino appearance-only oscillations

MiniBooNE finds a discrepancy at energies below the oscillation analysis range:

- currently not understood and under investigation

MiniBooNE's Next Steps

- Oscillation analysis paper posted in the archives (*arXiv:0704.1500*)
- Papers to follow in the near future, supporting this oscillation analysis:
  - Measurement of ν_μ charged-current, quasi-elastic interactions
  - Measurement of neutral-current π^0 production
- Further analyses of electron candidate events will follow:
  - combine merits of two present analyses
  - address more general models explaining the LSND anomaly
- Results from MiniBooNE's ongoing antineutrino running